Benchmarking Residential Energy Use

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ABSTRACT

Interest in rating the real-life energy performance of buildings has increased in recent years, and real-life efficiency performance rating of buildings is important for any sustainable energy future. Work on rating commercial buildings energy performance has shown important promise for helping increase commercial sector energy efficiency. Since residential buildings account for over half of all buildings-related energy use in the United States, methods to rate residential energy performance should also be important. Initial work on the 1993 Residential Energy Consumption Survey has been conducted to examine issues and approaches for residential energy performance rating tools, and some of these issues and approaches are presented in this paper. A method is presented for developing an energy performance rating or ranking procedure for residences in the United States based on regression analyses covering the entire residential sector, which covers mobile homes to apartments in large buildings. The same approach could be applied to subsets, such as single family detached houses. Significant additional work on the best methods to use to rate residential energy performance, causes of high and low performance, and other applications of these methods is needed.

Introduction

Some important activity on rating the measured energy performance of existing buildings has occurred over the last few years, as witnessed by the work on energy benchmarking (Sharp 1996; 1998) and the advent of the Environmental Protection Agency's (EPA) Energy Star Label for office buildings and schools (see their website at http://www.epa.gov/buildings/label/).

As Sharp (1996) stated, "Energy benchmarking offers initial building energy performance assessment without rigorous evaluation. 'Seeing' that building energy use is excessive is the first step to change."

The EPA Energy Star label website states the following, "The ENERGY STAR criteri[on] is a reflection of the distribution of energy performance in the commercial buildings market, as derived from data contained in the Energy Information Agency's (US Department of Energy) Commercial Buildings Energy Consumption Survey (CBECS). CBECS is a national, statistically based survey on building features, energy consumption, and expenditures in US commercial buildings. The primary drivers of building energy consumption and their relative impact on energy consumption were identified using CBECS data through a process commonly known as a step-wise linear regression. For each identified driver, or variable, the regression calculated the mean value (e.g., the average value for the driver) and the coefficient (e.g., the magnitude of the driver). These values were combined to form the benchmarking algorithm that takes user-defined actual values for a given building to compute a customized energy performance level representative of the performance of the top 25 percent -- the ENERGY STAR Target."

The US Dept. of Energy (DOE) has tools available on different websites around the country that allow the mean energy use of buildings for certain categories of building stratification to be calculated for both residences and commercial buildings, based on national survey data. [if website links hold up, readers can start at: http://www.eren.doe.gov/ buildings/energydata.html, and follow links on this page to either commercial or residential tools under Interactive Building Energy Data Tools.] This stratification approach is a simpler approach to estimating benchmarks, and can be very useful in many types of analysis, but it lacks the power of a regression analysis to achieve benchmarking algorithms applicable on a broader scale.

In Europe, efforts have also started to do some types of emissions benchmarking and implement voluntary agreements between governments and large corporations or industry groups to reduce air emissions (often by increasing energy efficiency, see for example, OECD 1997). The term "voluntary agreement" or "voluntary approach" has been used to describe a wide range of actions, including covenants, negotiated agreements, self regulation, codes of conduct, and eco-contracts.

In the Czech Republic, "Labels" of actual, measured energy performance are being tried for apartment buildings, and there appears to be the possibility that such labels may be legislatively required in the future (SEVEn 1999).

In contrast to rating performance based on actual, measured data, there are many tools available that estimate expected energy performance of buildings based on engineering models, some with correction against actual measured usage, e.g., DOE-2, Home Energy Rating Software, etc. However, it is beyond the scope of this paper to attempt to describe the variety of such available tools.

Much of the energy performance benchmarking work is directed at commercial buildings or large commercial enterprises. Because residential buildings account for over half of all buildings energy use in the United States, an effort was started by the authors to assess the feasibility of developing an energy performance rating (benchmarking) tool for residences based on actual measured energy consumption. The initial development, issues raised by the work, and possible future work needed are described here.

Background

One of the options for factoring out variations in energy performance among residences is to develop different distribution profiles of performance for different strata of residences. One key stratum is often region of the country. As this work on examining options for a residential performance rating tool was beginning, several requests were received for simple distributions of residential performance for specific regions of the country, specific types of housing, and specific main heating fuel. This approach is similar to what is offered by the DOE with their interactive building energy data tools, except that a distribution is provided instead of just a mean value for the stratum.

Performance rating could be done many ways. The EPA Energy Star label for buildings uses a scale of 1 to 100, with a rating of 75 or greater required to qualify for a label. However, the rating of 1 to 100 can be obtained simply by using the rating tool (see above). The scale of 1 to 100 indicates a position within a distribution, which is more definitive than comparison to a simple mean and more appropriate for distributions that are not statistically normal. Building energy use distributions are almost universally not normal.

While stratification can be useful in developing performance rating tools, an additional useful approach is normalization that factors out effects that might be considered exogenous to the desired performance to be measured. For example, for residences, the effect on energy use caused by the number of people in the household should probably be factored out of the overall performance rating. There is always a certain amount of subjectivity in deciding what should be considered exogenous in such adjustments, so some important decisions have to be made that impact any analysis or analysis results examining energy performance rating systems.

It should be noted that analysis beyond simple benchmarking may typically be needed to identify the causes of performance ratings being high or low or in the middle. Such analysis is important to achieving improved performance. Benchmarking can serve to spur interest in achieving improved performance, track performance over time, or justify rewards.

A data set was needed to explore the possibilities for residential energy performance rating approaches. If potential exogenous factors are to be examined, the data set should cover a wide range of information in addition to energy use. In his work on energy benchmarking, Sharp (1996, 1998) demonstrated several types of normalization using the CBECS data on commercial buildings. For the residential analysis presented here, a similar DOE data base on residential buildings (identified below) was considered the most useful.

Since 1978, the Energy Information Administration of DOE has used the Residential Energy Consumption Survey (RECS) to collect data on how households in this country use energy. The most recently published survey was conducted in 1993, although the detailed data for 1997 are now available. Detailed data from the 1993 survey became available in the Summer of 1999. The data cover household and housing unit characteristics, annualized 1993 fuel consumption and expenditures by end use for five fuels, and estimates for energy end uses such as space heating and cooling, lighting, water heating, and appliances. The housing unit data also contain information on energy-related characteristics of the house structure as well as weather data.

The 1993 RECS contains records for 7,041 households in the lower continental 48 states and the District of Columbia. (Surveys for households in Alaska and Hawaii were removed from public use data files for confidentiality reasons.) The households were weighted to represent 96.1 million households as of July 1993.

Energy Use Distributions of the 1993 RECS Data

One of the options for factoring out variations in energy performance among residences is to develop different distribution profiles of performance for different regions of the country. Relative to the requests for residential performance for specific regions of the country, specific types of housing, and specific main heating fuel, the resolution of the data in the 1993 RECS does not allow much stratification in this manner, but some acceptable results can be obtained for certain limited segmentation. One of these requests is described below to indicate the concept.

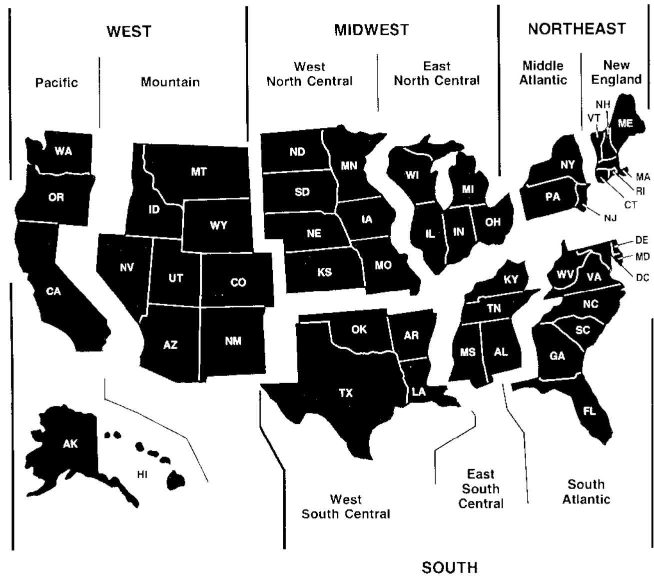

Figure 1. Nine Census Divisions

The lowest geographic resolution of the RECS data is Census division, of which there are nine (see Figure 1). Requests for distributions of energy use for specific housing configurations in specific locations are received regularly. The example of one request came from a builder in the Mountain Census division who was trying to understand the range of energy use in housing in their area. After some discussion, a distribution was developed for energy use per square foot (EUI, for Energy Use Index) for single family detached housing in the Mountain division that used gas as the main heating fuel. The distribution is shown in Figure 2. The energy use is calculated based on primary energy, where electricity is converted at 10,280 Btu/kWh. Previous work on EUI distributions (Sharp 1998) indicated that electricity use should be converted as primary or source energy, where the losses associated with generation, transmission, and distribution of electricity are included in the total energy for a building.

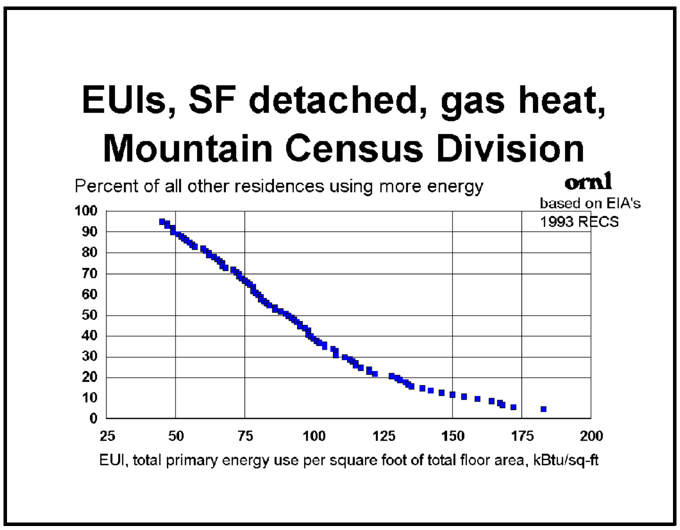

Figure 2. Single Family EUIs for the Mountain Census Division

Examination of this distribution shows residential EUIs covering from the 5% point to the 95% point (percent of residences that have a higher EUI). Note that there is no correction for heating degree days or any other factors. This distribution can be used to determine where the EUI for a specific residence in this 8-state area ranks relative to other single family, detached residences that use gas as the main heating fuel. This approach does not consider any normalizations for factors considered exogenous to energy performance, except that energy use is normalized to total floor area of the residence.

This example is provided to demonstrate the basic idea behind simple distributional rankings for the purpose of determining energy performance. One difficulty with the approach of using specific distributions for comparison of EUI (or total energy use) is limitations of the data set to cover extended detail. As more factors, such as heating system type, are added, the sample size becomes smaller and smaller, which makes the distribution less and less continuous and harder and harder to use.

Overall, the use of basic distributions is fairly simple and provides much more information than a simple mean of the distribution. Drawbacks include the use of ad hoc selection of stratification factors, based on what someone thinks is important, and the lack of normalization for potentially important factors that may be considered exogenous to energy performance but impact total energy use, such as the number of household members mentioned previously (see also Sharp 1998).

Floor Area Normalization

If EUI is selected as an initial indicator of energy performance, the amount of variation explained by the EUI itself should be determined. Using the 1993 RECS data, simple linear regressions of total household energy use vs both total and heated floor areas were performed. The data were weighted to reflect lower-48 U.S. households (96.1 million). The R^2 value for these two regressions were 0.436 and 0.418, respectively. (R^2 is the coefficient of determination, the proportion of variation in the independent variable that is accounted for by regression on the dependent variable.)

These results indicate that total energy use in US residences correlates better with total floor area than with heated floor area (space heat is less than 40% of total energy for the country). Since total floor area is easier to define and determine than is heated floor area, the use of total floor area for benchmarking residential energy performance appears more useful and prudent.

Plots of the raw 1993 RECS data on energy use vs total floor area were fan-shaped and indicated some lack of normality in the data. The scatter plot of energy use and total floor area is shown in Figure 3. Analysis showed that log transformations of both total energy use and total floor area provided the most reasonable representation of the data for

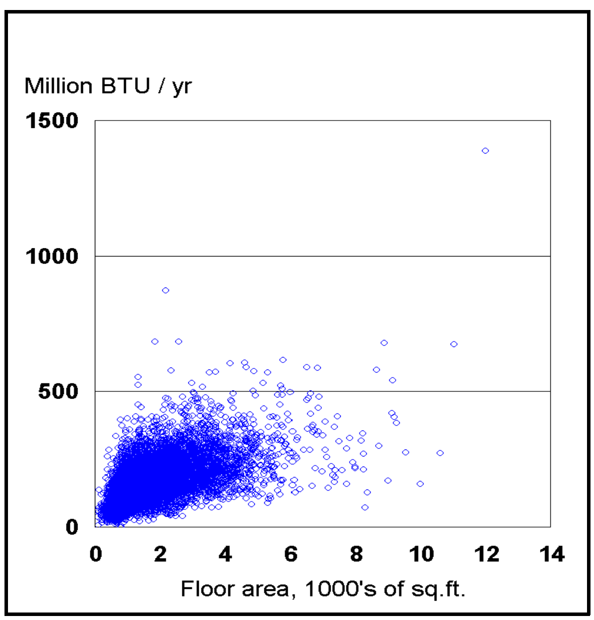

Figure 3. US Residential Energy Use vs Floor Area of Residence

a linear model (Figure 4). The R^2 value for this regression was 0.5005. These results show that the natural log of EUI (lnEUI), which is the natural log of energy use minus the natural log of floor area, accounts for about half of the variation in energy use for all US households.

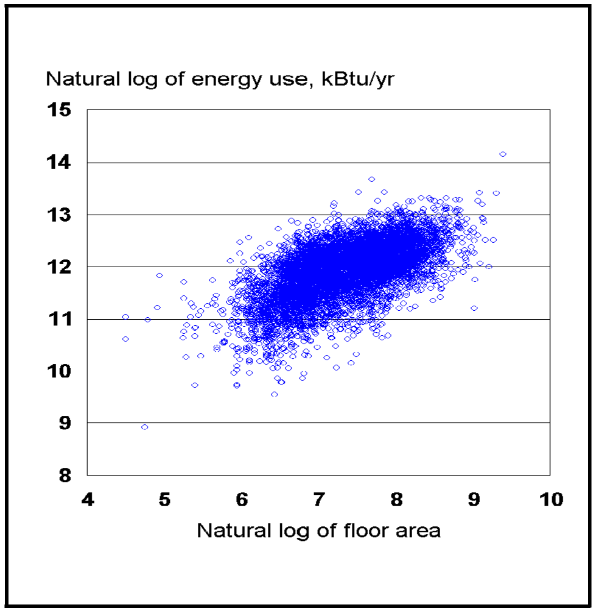

Figure 4. Natural Log of Total Energy Use vs Natural Log of Total Floor Area

Models to Normalize lnEUI to Allow EUI Ranking

The explanatory power of EUI for residences is significant. Further analysis was conducted to explain variation in lnEUI. Stepwise multiple linear regression with backward elimination was used, with the variables weighted to reflect total lower-48 U.S. households (96.1 million). Note that this includes ALL households: mobile homes, single family detached and attached, 2-4 unit buildings, and 5+ unit buildings.

Initial analysis indicated that variables to represent the geographic region of the country would be worth including in any normalization model of lnEUI. New logical variables were created to indicate inclusion either in or not in each of the nine Census divisions: New England, Mid-Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific.

After each regression, variables with the lowest R^2 values were eliminated (backward elimination). Several variable transformations were tested where the potential arbitrary nature of the values was a concern, as in the cases when a characteristic may be able to explain variation in energy use, but the data values assigned in the RECS are not necessarily aligned with expected influence on energy performance (examples given following).

Several variations in regression model specification are possible, especially depending on which factors one wishes to consider exogenous to the energy performance rating. Two specific model specifications are covered in this paper: one developed without the unit cost of energy, and the other including unit cost of energy.

Model 1 — Without Cost of Energy

Model 1 was developed from an initial set of about 40 variables, including nine logical indicators of Census division, several factors on income level, some housing characteristics variables, and some social characteristics of the head of household. The unit cost of energy ($/MBtu of source energy) was NOT included.

Successive elimination steps led to selection of a model with eight parameters other than the regional variables, and seven regional adjustments (Table 1). The partial R^2 of this model of lnEUI was 0.24, so the overall model R^2 for model 1 includes the variation in performance explained by lnEUI and the variation in lnEUI explained by model 1, which is approximately 0.50 + 0.24 x [1 – 0.50] = 0.62

Table 1. Regression Parameters Selected for Model 1 of lnEUI, kBtu/sq-ft-yr

Variable	Parameter Value	multiplied by	Partial R^2
Intercept	4.280	NA	
Foundation type	0.009	values from 10 - 70	0.0866
Pacific	− 0.177	0 or 1	0.0580
Year of construction	− 0.029	category from 1 to 14	0.0245
Number of household members	0.050	actual number	0.0242
Number of windows	− 0.010	actual number	0.0129
Type of residence	− 0.034	values from 1 to 5	0.0111
West South Central	0.252	0 or 1	0.0086
Mid Atlantic	− 0.032	0 or 1	0.0042
Heating degree days, base 60F	0.000032	actual value for year	0.0049
East South Central	0.188	0 or 1	0.0038
South Atlantic	0.108	0 or 1	0.0023
Below 100% of poverty level	0.059	0 or 1	0.0019
East North Central	0.056	0 or 1	0.0010
Air conditioning used	0.023	0 or 1	0.0004
Mountain	0.038	0 or 1	0.0003

Many interesting issues are raised by these results related to whether parameters should be considered exogenous or not. The interest in this analysis is ranking of lnEUI for individual households without accounting for specific efficiency factors or technologies, and instead accounting only for significant factors that are outside the boundary that would impact energy efficiency directly. Such decisions can be, and at times are, arbitrary, but at the least, differing policy perspectives can strongly influence consideration of what parameters should be considered outside this boundary or not. Decisions made for this analysis should not be considered as the "best," but instead represent only a view taken to complete an initial analysis.

In the initial regression results, the number of bedrooms and the number of bathrooms had partial R^2 values near 1%. Should these parameters be included? We decided to not include them. The number of windows showed results that appear counterintuitive: as the number of windows increase, lnEUI decreases slightly. Is this related to reduced lighting requirements? Is the thermal contribution of windows over an entire year positive? Should windows be included? We decided to retain the windows adjustment, although arguments could easily be made both ways.

The Census division parameters indicate how much each Census division differs from the overall sample. A parameter was retained for seven out of the nine divisions in this model, with only New England and the West North Central divisions not being statistically significant at the 0.05 level.

Adjustment of several of the RECS data quantities was necessary due to how missing values were coded, but in addition to this, there remains also the issue of the arbitrary nature of some of the values relative to potential impact on lnEUI. Two parameters remained in the model, where adjustments based on best engineering judgment were made to make them correspond better to lnEUI: type of residence and foundation type.

The type of residence is a value from 1 to 5, where 1 is a mobile home, 2 is SF detached, 3 is SF attached, 4 is 2-4 unit building, and 5 is 5+ unit building. Attempts to rearrange these values did not lead to any better results. The regression results show that expected lnEUI is highest for mobile homes and decreases to lowest for 5+ unit buildings.

Foundation types in the RECS include: Other, Basement, Enclosed Crawl Space, Open Crawl Space, Concrete Slab, Combination, Not Applicable, with corresponding codes of 0, 1, 2, 3, 4, 5, and 9. Regression results for these codes were not good. Alternate codes of 70, 20, 50, 40, 30, 10, and 60 yielded fairly good results, and foundation type became the strongest indicator of lnEUI variation. Whether this parameter should be included or not again depends on the purpose of the analysis. The most appropriate values to use constitute a much larger question that appears to deserve some research.

Heating degree-days and the presence of air conditioning provided some contribution to understanding variation in lnEUI in the regression for model 1. Heating is only about 35–40% of total residential energy use nationwide, heating energy and cooling energy tend to cancel each other out in the value of total energy for a year, many homes have little heating required, and some climate adjustment is contained in the regional parameters, so heating is not as prominent in explaining total energy use as many readers might expect.

In order to determine the energy performance ranking of a residence, either the regression model or a simplified model using mean values is applied. The lnEUI (or EUI if one wanted to convert) calculated by the model must be compared to the distribution of regression model results for the regression data set or to a mean-adjusted distribution to obtain a ranking. The regression equations are quite complicated and beyond what can be presented here. The mean adjustment approach is an approximation of the regression results but can be explained more easily.

In the mean adjustment approach, the mean values of the retained regression variables for the data set used for the regression analysis are calculated, and the mean values for each variable are entered in the regression model to obtain a “mean” result. For a specific residence, the actual lnEUI must be calculated, and a model lnEUI is also calculated using the regression model parameters. An adjustment ratio is calculated as the model lnEUI divided by the “mean” result. The actual lnEUI is then divided by the adjustment ratio to obtain an adjusted lnEUI. The adjusted lnEUI is compared to the distribution of model adjusted lnEUIs obtained for the entire data set to determine the percentile position in the distribution. The percentile position becomes the rating.

For the 1993 RECS, the mean lnEUI for Model 1 is 4.58 (97.5 kBtu/sq-ft-yr), and some percentiles of interest for the mean adjusted lnEUI distribution are shown in Table 2. As an example, assume a residence has an actual lnEUI of 4.6 and a modeled lnEUI of 5.0. The adjustment ratio is 5.0/4.58 = 1.09 and the adjusted lnEUI is 4.6 divided by 1.09 = 4.22. The approximate percentile rating is 83.

Table 2. Model 1 lnEUI Percentiles

Percentile of those using more energy	lnEUI
5	5.21
10	5.08
25	4.84
50	4.58
75	4.33
90	4.09
95	3.96

Model 2 — With Cost of Energy

One significant factor that may be considered exogenous is the unit cost (or average price) of energy. Arguments can be made as to whether the influence of this factor should be included or not when ranking the relative efficiency of an EUI for a building. One argument for inclusion is the need to estimate economic response to energy pricing and factor it out. However, since increased unit cost shows a requirement to have even better energy efficiency performance in order to receive a higher rating, some may not wish to add this adjustment.

A second model (model 2) for ranking lnEUI was developed that included this factor. Inclusion of the cost of energy did not change the model parameters much, except that the new parameter for unit cost of energy was added, the relative importance and parameter values of the other parameters were modified, and there is some shifting of regional parameters (Table 3). The partial R^2 of this model of lnEUI was 0.26, so the overall model R^2 for model 2 is approximately 0.63.

Table 3. Regression Parameters Selected for Model 2 of lnEUI, kBtu/sq-ft-yr

Variable	Parameter Value	multiplied by	Partial R^2
Intercept	4.750	NA	
Foundation type	0.009	values from 10 - 70	0.0866
Pacific	-0.261	0 or 1	0.058
Unit cost of energy ($/MBtu)	-0.045	$ per Million Btu	0.0325
Year of construction	-0.028	category from 1 to 14	0.0251
Number of household members	0.051	actual number	0.0255
Number of windows	-0.010	actual number	0.0159
West South Central	0.142	0 or 1	0.0081
Type of residence	-0.035	values from 1 to 5	0.0058
Below 100% of poverty level	0.064	0 or 1	0.0023
Mountain	-0.048	0 or 1	0.0012
West North Central	-0.050	0 or 1	0.0007

Heating degree days, base 60F	0.000011	actual value for year	0.0005
Air conditioning used	0.027	0 or 1	0.0006
New England	0.033	0 or 1	0.0002
East South Central	0.042	0 or 1	0.0001
South Atlantic	0.029	0 or 1	0.0003

The regional adjustments cover several factors, probably including some weather adjustment and some adjustment for adaptation to cost of energy. When cost of energy is added to the regression, the regional adjustments change, including the regions with no adjustment. For model 1, adjustments for New England and West North Central were not included in the model, while for model 2, these two regions are statistically valid, while two other regions, Middle Atlantic and East North Central do not differ enough to have separate adjustments.

Potential Bias for Floor Area Based Models

Initial testing of the results obtained for these two models showed robust behavior and good ability to show rankings of energy performance of residences based on lnEUI. However, the testing also showed a strong bias toward allowing larger residences to use more energy for the same number of people living in the household. This result indicates that, although the model corrects for the number of people in the household, the model allows larger energy use per person as floor area increases. This appears to be a natural consequence of normalizing by floor area initially and a trend (buried in the model) toward increased energy use per person in larger residences. A linear regression of the natural log of energy use per person on natural log of total floor area shows a slope of 0.33 (lnEUP increases 0.33 for every increase of 1 in log of floor area), with an R^2 of 0.11.

As an example, assume a family of four living in a 2,000 square foot single family house is transplanted to a 3,500 square foot house. If the rating in their 2,000 square foot residence were about 65, their rating in the 3,500 square foot house would be 80 or greater. Granted there are many uncertainties about increased energy for heating and cooling, but the evidence so far suggests strongly that using EUI as an indicator of efficiency will give disproportionately higher ratings to larger houses.

Conclusion

A method for developing an energy performance rating or ranking procedure for residences in the United States has been presented. The method used the 1993 RECS data to perform regression analyses on energy use of residences and obtains model parameters for the entire residential sector, which covers mobile homes to apartments in large buildings. The same approach could (and probably should) be applied to subsets, such as single family detached houses.

Although the work presented here demonstrates a method for developing such rating procedures, the details of the approach require more development. Possible rearrangement of data values to provide the best regression results is probably needed for some parameters, e.g., values for foundation type could probably be improved if foundation type were desired in an analysis. The year of construction data could probably be adjusted to provide better results also. Additional parameters that were not considered here may also be of value. Since the 1997 RECS data are now available, their use in such analysis could be pursued.

Model parameters are presented for two models of log-based floor area normalized energy use (lnEUI), with overall regression coefficients of about 0.6 – 0.65. The two models cover the cases of the cost of energy included or excluded. Limited initial testing indicates that floor area normalized results appear to have a bias toward allowing families in larger houses to possibly use disproportionately more energy per person than those in smaller houses.

Using either model 1 or model 2 as a baseline, the required characteristics information, together with EUI for specific residences, can be used in a rating procedure to give an energy use performance rating from 1 to 100. Percentile distribution data for model 1 are given in this paper ranging from the 5th to the 95th percentile of residences having higher adjusted lnEUI.

Significant additional work could still be conducted in this area to empirically determine and/or analyze:

- appropriate approaches that appear to have the least bias in rating energy performance
- results for subsets of the residential sector
- causes of high and low EUIs after correction for the model parameters
- significant parameters for data sets covering specific geographic areas (e.g., cities) for comparison of results with the national models
- residential designs that truly lead to efficient EUIs for TOTAL energy use as opposed to just heating or just cooling energy
- required EUI improvement scenarios needed to meet national air emissions reduction goals

References

OECD 1997. *VOLUNTARY AGREEMENTS WITH INDUSTRY*, *Annex I Expert Group on the United Nations Framework Convention on Climate Change*, Working Paper No. 8, Unclassified OCDE/GD(97)75, Paris: ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (also try http://www.oecd.org/env/docs/cc/gd9775.pdf).

SEVEn 1999. "Energy Audits for Kladno," *News at SEVEn* (English version), Vol 7, No 4 (Dec 1999), Prague: SEVEn, 120 56 Prague 2, Czech Republic, email:seven@svn.cz, Fax: +420-2-2424-7597

Sharp, T. R. 1996. "Energy Benchmarking in Commercial Office Buildings," *Proceedings of the 1996 ACEEE Summer Study*, pp 4.321–4.329, ACEEE: Washington, DC..

Sharp, T. R. 1998. "Benchmarking Energy Use in Schools," *Proceedings of the 1998 ACEEE Summer Study*, pp 3.305–3.316, ACEEE: Washington, DC..