Social and Engineering Models of Residential Energy Consumption: An Empirical Examination

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Abstract

While differences in residential energy consumption have been identified between households along lifecycle, social class and cultural dimensions, residential end-use demand models commonly consider only architectural, HVAC, family size and price/income variables. To examine both social and engineering influences on residential consumption, the California Energy Commission's residential end-use demand forecasting model was fit to electricity and gas consumption data on 3600 San Diego households, along with measures of family form, income, home ownership, length of residence and education. Census measures of neighborhood character (ethnicity, poverty, social class, age composition and immigration rates) were also incorporated in the models.

After controlling for household differences in dwelling size and type, insulation levels, systems, appliances and number of household members (the engineering variables) large and significant differences in household electricity consumption between social groups were identified. These differences represent differences between household types which are unmeasured in the engineering model. Comparisons of alternative engineering and social models, suggest that each of these sets of variables, while highly correlated with the other, makes a distinct and important contribution to predicting residential energy use. A theoretical model of the independent and joint contributions of engineering and social factors to the explanation of variations in residential energy consumption is presented.

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Two kinds of models are in common use in residential energy planning and research: (1) simulation models of building energy performance and occupant behavior (in which assumptions about the thermodynamics of materials, HVAC and appliance efficiencies, and the energy use rates of individuals are used to estimate the energy consumption of dwellings), and (2) statistical models of energy use (in which the measured characteristics of dwellings, component systems and consumer households are used to explain their energy use and to estimate population consumption levels).[1] Simulation models (e.g. DOE2) typically include detailed specifications of building dynamics ("engineering variables"), as well as less-precise treatments of occupant energy-using behaviors ("social variables"). Statistical models, on the other hand, tend to include more approximate specifications of dwelling characteristics, household demographics and environmental variations.[2]

A central conceptual problem in statistical modeling of residential consumption lies in the relative emphasis given to the engineering (e.g. dwelling size, furnace type) and the social variables (e.g. household size, age of head) in the prediction equations.[3] A high degree of correlation between these two sets of factors (e.g. smaller families tend to live in smaller dwellings; higher-income families tend to live in newer dwellings) allows both to serve as rough proxies for the activities of persons (and the performance of machines and structures involved in those activities) that are the sources of energy flows. The observation that highly detailed, joint engineering and social models of consumption (statistical and simulation models) are both desirable and feasible has produced at least one such specification proposal (e.g. Parti, Sebald and Won 1986). But lack of readily-available residential consumption data which include reliable measures of dwelling characteristics, appliance stocks and household demographics has hampered efforts to construct such models.

1 Throughout the discussion we use the term "dwelling" to refer to the physical structure (including the building envelope and associated mechanical systems), and "household" to refer to the persons (a social unit) occupying the dwelling.

2 The performance of both types of models can be less-than-impressive when applied to cases of actual residential energy consumption (Hackett, et.al.,1984).

3 Typically linear regressions of energy consumption on a set of engineering and/or social predictor variables, taking the form: $Y = a + b_1(X_1) + b_2(X_2) \ldots + b_n(X_n) + e$

where:
- Y = energy consumption
- a = intercept (constant)
- b_n = regression coefficients (slope)
- X_n = predictor variables (engineering/social)
- e = error term

Simulation and statistical modeling of both "engineering" and "social" sources of residential consumption are very closely related in the case of end-use energy demand forecasting models, however. These simulation models incorporate estimates of typical energy consumption attributed to end-uses which are reasonably believed to be major components of residential consumption (e.g. space heating and cooling, cooking, clothes washing, television watching). The particular values used may be obtained from engineering experiments, appliance simulations, or sub-metering studies, but are often estimated using statistical models (often referred to as econometric conditional demand equations) of the relationship of consumption to the presence of particular end-use appliances. Correct specification of those regression models, in turn, has policy ramifications for demand forecasts —particularly when they are used as bases for regulatory decisions about power plant siting and energy pricing.

The research reported here addresses the relationship between engineering and social specifications of residential electricity consumption, in the context of end-use forecasting. Forecasters' concern for accuracy in predicting future demand fosters an interest in understanding present energy use patterns, and therefore also supports the collection of survey and consumption data of sufficient quantity and quality to allow a detailed examination of engineering and social components of energy consumption in the context of a single model.

This paper (1) presents the results of our analysis of a major end-use demand model fit to actual residential consumption data; (2) reports the results of a combined social/engineering model of residential electricity consumption; and (3) proposes a theoretical approach through which the relationship between these two set of factors may be further analyzed and differentiated.

Problem

In line with the shift toward an "end-use" orientation in residential energy demand forecasting (and the current interest of energy suppliers in the "demand side" of energy flows), utilities more or less routinely conduct customer surveys to gather information about the characteristics of housing units, consumer demographics and appliance stocks in their service territories. These sampled inventories of housing types, end-use appliances and family sizes may be used to generate baseline values for demand simulation models. Projections of new construction, population growth and appliance saturation changes are then used to estimate future aggregate levels of energy demand.

The California Energy Commission's (CEC) residential energy demand model was one of the earliest, and most ambitious, of these end-use simulation and forecasting systems. It has become a key element in California's regulation of energy prices and power plant siting. Because the accuracy of that model is of interest to policy-makers, as well as to energy suppliers and consumers, the CEC has undertaken a study of inputs to the model which includes the research reported here. While most directly concerned with the design and performance of the California model, our results are also relevant to end-use models, under development, and in routine use, elsewhere. We were interested in (1) whether the "end-uses" of residential energy, as represented by these models, adequately account for observed residential electricity and natural gas consumption; and (2) whether measurements of differences in the energy consumption betweeen consumer subgroups (differences not captured in engineering model) might be used to improve those models' fit to actual energy use.

The CEC model produces utility-area estimates of future residential energy demand, employing inputs of information about historical weather conditions, appliance saturations, family sizes, housing unit sizes and consumption levels and projected rates of change in those areas. The model first estimates annual consumption for each of twelve end-uses (within a number of disaggregated housing type, vintage and climate zone subgroups),[4] and then aggregates those estimates into projected total demand for each of 20 future years, in each California utility service territory. The model assumes average rates of appliance use (and efficiency), within each disaggregation group —using average "unit energy consumption," ("UEC") estimates for electricity and gas used in cooking, space conditioning, water heating, for example, by "households living in single-family, detached dwellings built prior to 1973 in a particular climate zone."

These estimates of appliance consumption averages for large subpopulations (e.g. those of "all residents of detached houses built before 1970"), regardless of whether those averages are obtained through field measurements, engineering simulations or statistical estimation techniques, obviously mask large energy consumption differences between households. It might well be the case that residential consumption is not best disaggregated into housing type, vintage and climate groups, but along more social lines. In fact, the literature on social or "lifestyle" group consumption differences between households lends support to a variety of other dissaggregation strategies (e.g. dividing the population into social categories which might include: the elderly, low-income, ethnic minorities, rural, urban, single parent families, etc.).[5] One goal of our research was to explore possible alternative consumer subgroup disaggregation schemes.

Now it could also be argued that social disaggregation is not warranted, that the CEC model is adequately specified and that its average consumption values (UECs) for end-use appliances (air conditioners, dishwashers, freezers, etc.) may, as a practical matter, represent fairly stable estimates of the "typical" consumption attributable to those appliances (around which individuals' particular rates of use will, of course, vary idiosyncratically). If that were the case, regression equations which replicate the forecasting model's specification of demand determinates (e.g. housing type and size, presence of end-use appliances, number of household members, etc.) may be fit to real-world consumption data with several expected results. First, the bulk of variation in electricity and gas consumption should be explained by the forecasting model variables, with unexplained variation attributable only to measurement error

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4 In San Diego County, for example, the model estimates separate consumption levels for twelve disaggregation subpopulations: one for each combination of three housing types (single family detached, multi-family, and mobile home units) with four vintage periods (pre–1975, 1975–1978, 1979–1983 and post–1983).

5 Arguments for attention to the energy consumption differences between of social/lifestyle groups have been advanced by Olsen (1981), Stern and Aronson (1984) and Stern (1986). Studies of actual consumer behavior which suggest residential energy use differences between subgroups of consumers are reported in the work of: Fagerson (l984), Diamond (l984), Erickson (l984), and Kempton (l986). Consumption differences along age, social status and ethnic dimensions are suggested by Morrison, et. al. (1979), Fritzsche (1981), Frey. and LaBay (1983), Throgmorton and Bernard (1986), Hackett and Lutzenhiser (1986;1988), and Hackett (1987).

and random, unmeasured events related to energy consumption. Second, the addition of social or lifestyle variables to the equation should not produce statistically significant or large coefficients for those variables. If it is simply the case that older single persons, for example, are more likely to live in small apartments and not to own freezers, then their energy consumption profiles may be adequately accounted for by the additive combination of coefficients estimated for those factors alone: multi-family unit, small size, no freezer, and a one-person water heating term. Including a variable in the prediction equation which identifies older single persons would contribute nothing to our understanding of their consumption habits which was not contained in the previous equation. The regression slope for that variable would not be statistically significant, and the estimated value of its coefficient (the consumption difference between older singles and other consumers, controlling for engineering determinates of consumption) would not be large.

To test the performance of the CEC engineering model with respect to observed consumption, we first recoded sample cases dwelling, appliance, conservation and household size identifiers to correspond to the specifications of the CEC model. Next, we estimated a series of regression models of annual electricity (kWh) and natural gas (therms) consumption on the CEC model variable set. We then added measures of household composition, income, education, tenure (length of residence), home ownership and neighborhood ethnicity as independent variables to the models, to test for social sources of additional variability in the population.

The simulation model's fit to the data was good --by social science standards (R^2=.59). However, many of the measures of social subgroup differences were also statistically significant ($p < .01$) and as large or larger than the coefficients estimated for the engineering variables. While the addition of those terms to the equation did not produce a dramatic improvement in explained variation in consumption (R^2=.64), comparisons of alternative social and engineering models of consumption suggest that the variables used in these two views of energy use are highly correlated with one another. This result raises questions about the quality of the engineering end-use model's fit to the underlying patterns of energy-using activity for which its terms are assumed to be adequate proxies.

Data

We used the San Diego Gas and Electric Company's (SDGE) MIRACLE VI customer survey, and associated energy consumption records, as our primary data. MIRACLE VI collected data on household appliance stocks, dwelling characteristics, customer conservation activities and retrofits, and household demographics, from a stratified random sample of 7600 San Diego County households in the latter part of 1983. San Diego has a mild climate, which varies relatively little across the county in temperature at any given time (additional micro-climate measures were also included in the data). SDGE's residential customers had not experienced any price changes during, or immediately prior to, the data collection period. The potentially confounding effects on consumption of both weather and price differences between cases were effectively controlled in this sample. Case-level measures of monthly electricity and natural gas consumption (from utility billing files) had been merged with survey data and aggregated into annual (kWh and therm) consumption variables. To enrich the limited number of social variables available for analysis, 1980 Census tract-level measures of neighborhood social status, immigration and ethnic characteristics were assigned to individual cases.[6]

Comparisons of the MIRACLE VI sample with the 1980 Census indicate that response to the survey was biased toward households with higher incomes and higher levels of education. In addition, persons who had lived at the surveyed addresses for fewer than five years and renters, particularly those living in smaller apartments (one bedroom or less), were significantly underrepresented in the sample. These biases are correlated with residential energy consumption and certainly result in overstated estimates of population-level consumption when calculations of aggregate values are made using the unweighted sample.

Forecasters and others who work with these sorts of utility survey data are also familiar with their characteristically high rates of non-response to certain questionnaire items (e.g. questions regarding income, dwelling size in square feet and insulation levels).[7] Our analysis required that cases missing responses on dwelling size, income, and number of household members be excluded, an adjustment which resulted in a reduction of sample size by nearly 50% (from 7600 to less than 4000 cases). This reduction further biased the sample in favor of cases with higher rates of energy consumption, higher incomes and larger dwelling sizes. In addition, when Census neighborhood measures of proportions of minority residents (Asian, Hispanic and Black) and recent immigrants are compared to the neighborhood locations of cases excluded because of item non-response, the evidence suggests that these groups may also be underrepresented in the truncated sample.

While missing data of these sorts pose serious problems for estimation of aggregate population-level consumption, as long as the types of consumers excluded from the sample are not radically different (along unmeasured dimensions) from some cases included in the sample, then the estimates of the regression coefficients and their standard errors will not be biased. In other words, the proportions of household types in the sample may vary considerably from the population proportions without biasing the relationships between household types in terms of their energy consumption, in either the sample or the population. Even halving a sample of this size leaves substantial numbers of low-income, short-tenured, small apartment dwellers and other low-consumption households in the sample.

Analysis

Our analysis first specified, for each case in the subsample, those dwelling, appliance and household characteristics used in the CEC residential model, produc-

6 While this approach obviously flirts with the "ecological fallacy," geographers, sociologists and other researchers have repeatedly confirmed the common-sense observation that U.S. residential neighborhoods tend toward class homogeneity --with the standard caveats regarding transition areas and the natural aging of neighborhoods, of course. In any event, the addition of Census variables offered little improvement to the models under consideration. Neighborhood ethnic proxies were included, however, in the final models.

7 These response selectivities have been examined, in this and similar samples, in some detail (UC-ERG,1988).

ing a set of 56 end-use measures and interaction terms which we identified as the "CEC base model variable set." We then tested this model on the San Diego data (taking the appropriateness of the CEC specification as given) and estimated its goodness of fit. Because the CEC model forecasts demand for disaggregated housing types and vintage groups, we then tested the utility of those housing type/vintage disaggregations in the San Diego case. We also tested other potentially useful architectural and climatic disaggregations; constructed and estimated the relationships of a variety of social, geographic and cultural measures to the CEC model's "residual (unexplained) consumption"; estimated hybrid engineering/social models of electric and gas consumption; examined correlations between social and engineering sets of consumption predictor variables; specified a number of alternative consumption models; and compared the results of aggregation from these models with known population values.

The details of those analyses are not reported here, however a brief survey of their findings are in order, followed by a more detailed presentation and discussion of an exploratory hybrid social/engineering model of residential electricity consumption.[8]

- The effects of housing vintage are evidenced by the declining average consumption of dwellings built under successively more stringent energy conservation requirements of building codes (beginning in 1975), suggesting that the CEC model's vintage period specifications are reasonable.

- Significant and large differences were observed between <u>subtypes of multi-family units</u>. Condominiums, townhouses, multi-plexes and apartments differ considerably from one another in average consumption, with some behaving more like single family units. The CEC model might usefully improve its distinction between housing types (currently a simple division of units into "single family detached" and "multi-family" types) by taking these differences into account.

- The CEC model's specification of the effects of <u>dwelling size</u> (square feet) on heating and cooling loads, and of <u>household size</u> (number of persons) on water heating, cooking, washing, drying, dish-washing and related loads, apparently do not exhaustively account for the correlation of these variables with either electricity or natural gas consumption. That is, building size and number of persons are also correlated with on energy use <u>independent</u> of their relationships with energy-using technologies.

- Although the CEC model assumes the effects of household size on electricity and gas consumption to be linear, they are significantly non-linear in the sample and are unlikely to be linear in the population.

- Specification of the effect of household size on consumption is improved by the addition of information about ages of household members, suggesting that the household size measure is also related to <u>lifecycle stage and family form</u>. Quite different consumption patterns were noted between household types, with the

8 For a more complete discussion see Lutzenhiser, Hackett and Schutz (1988).

CEC model specification significantly overestimating the consumption of some groups and underestimating that of others.

- A number of other social variables were also found to be significant predictors of electricity and gas consumption, controlling for the engineering specifications of the CEC model.[9] Household composition, household income, education levels of heads of household, owner/renter occupancy status, length of residence and geographic location were all found to be significant predictors of variations in consumption which were not captured in the CEC model. In addition, some cultural and social class variables associated with census tract-level ethnicity, immigration and migration, workforce status and occupation proxies seem to be related to gas and electricity consumption.

These results indicated a combined social/engineering model of residential energy consumption, and one such model (annual kWh consumption) is presented in Table I. Without discussing the slopes of the appliance variables in detail (the UECs), we note that when these UEC estimates are adjusted for behavioral/social variations between households, their values differ somewhat from those produced by the CEC model variable set alone, as well as from the estimates that the CEC simulation model actually uses.[10] The 1,022 kWh/yr intercept term in the electric equation (which, in this sort of model, represents lighting, small appliances, non-frost free refrigerator consumption, and other consumption not accounted for by the independent variables) also differs somewhat from the CEC model's "miscellaneous end-use" estimate minima of 700 kWh and 1,200 kWh for multi- and single-family dwellings, respectively.

The variations in consumption predicted by social variables are often fairly large. Although included throughout the CEC model variable set (in interactions with space conditioning variables), when dwelling size (this time as a correlate of social status) is again added to the model it is found to be strongly correlated with electricity consumption, accounting for an additional 952 kWh/year per 1000 square feet of dwelling floor area. Controlling for the CEC model's specification of household size (the simulation model includes interaction terms for numbers of persons in households with cooking, washing and hot water end-uses), household ifecycle groups (which incorporate an alternative measure of household size) also significantly differ from one another in annual consumption.[11] Couples, singles, small young families and families with relatively large numbers of children consume less than the middle-aged/middle-sized nuclear families who form the reference category. Multiple-adult groups, families with adults over 65 years of age, and families with adult children consume more than the reference group.

Income is also strongly associated with consumption, with the lowest income groups using less electricity, and the higher income groups considerably more, than the middle income ($20,000 - 30,000/yr) reference group. The relatively small

9 When social terms were entered in equations which already contained all of the CEC model variables.

10 For example, the CEC model uses a color-television UEC of 627 kWh/yr, while the CEC regression model variable set estimates 750 kWh/yr and the socially-amended model estimates 534 kWh/yr.

11 Neither of these sets of additional dwelling and household size terms are collinear with engineering terms already in the model.

Table I. Social/Engineering Electricity Demand Model

Dependent Variable: Annual kWh Consumption
R Square .643

	B	SE B	T	Sig T
CEC End-Use Model Variables				
Heat Pump	-4249.29	811.69	-5.2	.00
Elec Baseboard	-183.95	316.06	-.5	.56
Elec Furnace	-1973.05	663.60	-2.9	.00
Heat Pump_KSqFt	3230.00	360.00	8.9	.00
Baseboard_KSqFt	490.00	230.00	2.1	.03
Elec Furn_KSqFt	1850.00	400.00	4.5	.00
Ceiling Isulation	-28.71	98.49	-.2	.77
Ceil Insul_Elec Ht	266.94	274.25	.9	.33
Wall Insul	77.51	93.65	.8	.40
Wall Insul_Elec Ht	666.62	275.56	2.4	.01
Caulking	-66.86	86.58	-.7	.44
Caulk_Elec Heat	643.19	264.10	2.4	.01
Multi-Glazing	5.12	104.20	.0	.96
Mult Glazing_Elec Ht	432.86	337.36	1.2	.19
Central A/C	-325.45	356.01	-.9	.36
Window/Wall A/C	670.25	128.12	5.2	.00
Evap Cooler	994.10	434.81	2.2	.02
Cent A/C_KSqFt	870.00	180.00	4.6	.00
Elec Hot Water	1520.44	303.75	5.0	.00
Heat Pump Ht Wtr	937.93	969.44	.9	.33
Solar-Elec Ht Wtr	495.70	774.87	.6	.52
Wt Elec _Dshwsh_P/HH	126.51	118.60	1.0	.28
Wt HtPmp_Dshwsh_P/HH	315.52	457.77	.6	.49
Wt SolEl_Dshwsh_P/HH	230.38	414.55	.5	.57
Wt Elec _Clthwsh_P/HH	386.95	127.09	3.0	.00
Wt HtPmp_Clthwsh_P/HH	293.14	458.93	.6	.52
Wt SolEl_Clthwsh_P/HH	-46.39	441.27	-.1	.91
Wtr Htr Insul	-38.82	87.56	-.4	.65
Elec Wtr Htr Insul	780.96	278.32	2.8	.00
Low-flow Shower	34.35	84.13	.4	.68
Elec Wtr Low-flow	-339.64	282.81	-1.2	.22
Elec Range	229.84	182.55	1.2	.20
Elec Rng_P/HH	93.61	57.50	1.6	.10
Frost-free Fridge	518.18	116.65	4.4	.00
Freezer	1008.73	90.09	11.1	.00
Elec Clothes Dryer	190.27	205.80	.9	.35
Elec Dryer_P/HH	132.34	63.50	2.0	.03
Color TV	533.59	151.48	3.5	.00
Water Beds	569.94	76.18	7.4	.00
Dish Washer Motor	117.51	33.98	3.4	.00
Clothes Washer Motor	131.52	46.95	2.8	.00
Pool Pump	2291.82	131.46	17.4	.00
Missing Elec Rm Ht	196.86	225.37	.8	.38
Missing Elec Cnt Ht	182.14	250.20	.7	.46
Missing Elec Wtr Ht	-36.02	203.48	-.1	.85
Missing Dish Washer	80.85	221.02	.3	.71
Missing Clth Washer	-92.76	301.96	-.3	.75
Missing F-F Fridge	731.12	196.61	3.7	.00
Missing Clth Dryer	-122.98	126.46	-.9	.33
Missing Pool	614.30	253.53	2.4	.01
Built 1975-78	-52.56	119.36	-.4	.65
Built 1979-83	-501.20	150.43	-3.3	.00
Multi-family Unit	-226.32	118.89	-1.9	.05
Social-Cultural Variables				
Other KSqFt Effects	952.12	92.88	10.2	.00
Younger Singles	-771.01	252.87	-3.0	.00
Older Singles	-793.59	230.28	-3.4	.00
Couples	-287.91	183.54	-1.5	.11
3+ Adults Households	147.02	188.49	.7	.43
Small Young Families	-487.62	177.59	-2.7	.00
Many (3+) Children	-776.26	246.80	-3.1	.00
Older Families	96.62	226.12	.4	.66
Oldest Families	463.36	195.40	2.3	.01
< $10,000/yr	-379.97	156.46	-2.4	.01
$10,000-20,000/yr	-170.26	113.58	-1.4	.13
$30,000-40,000/yr	-93.03	113.59	-.8	.41
$40,000-50,000/yr	307.72	139.38	2.2	.02
$50,000-75,000/yr	654.58	147.36	4.4	.00
> $75,000/yr	1659.22	193.62	8.5	.00
Renters	277.22	129.93	2.1	.03
Tenure < 1 yr	-281.33	202.31	-1.3	.16
Tenure 1- 3 yrs	-111.16	109.53	-1.0	.31
Tenure 8-11 yrs	284.40	124.03	2.2	.02
Tenure 12-19 yrs	439.43	131.64	3.3	.00
Tenure > 20 yrs	321.52	137.41	2.3	.01
Educ < High School	99.26	171.42	.5	.56
High School Grad	323.17	118.83	2.7	.00
Tech School Grad	155.38	187.22	.8	.40
Some College	223.34	91.06	2.4	.01
Maritime Climate	60.80	87.22	.6	.48
Trans/Inland Climate	250.07	119.02	2.1	.03
% Hispanic	-75.36	523.18	-.1	.88
% Asian	-773.70	1281.51	-.6	.54
% Black	1178.84	676.10	1.7	.08
Missing Ethnicity	121.59	104.63	1.1	.24
(Intercept)	1022.85	348.79	2.9	.00

differences between most income categories, however, with much higher consumption levels estimated for higher income households, suggests that the CEC model's engineering variables better fit the middle classes than the economic extremes. This pattern appears to involve the conservative use of energy by lower income households and the presence of unmeasured appliances and the "non-conserving" uses of energy among higher income households. These results may better support a social class interpretation of the effects of income on consumption than they do a continuous and gradual income elasticity of demand interpretation, meaning, for example, that at some income levels the price of energy is not calculated at all.[12]

Concerning other social measures, renters (all paying their own utility bills) consumed somewhat more electricity than did homeowners --perhaps representing the lower overall quality and energy efficiency of rental housing. Education is also moderately related to consumption, with lower education levels associated with higher consumption. This finding can be interpreted as the effect of a correlation of lower education with poorer housing quality, quite as readily as evidence of some sort of a "more education = more conservation behavior" or "more education = better energy information" effect.

The effects of the ethnic proxies are interesting, particularly because the consumption differences between groups are similar for both electricity and gas. Consumption increases with the tract-level proportion of Blacks, while it decreases slightly with Hispanic proportion increase and drops quite strongly as the Asian population increases. These variables were imported from the 1980 Census and are not claimed to represent accurate case-level ethnic identification. Their correlation with residential consumption lends some support, however, to the findings of other studies which have used household ethnic/cultural information.[13] The direction and magnitude of these effects should, of course, be interpreted with caution.

Examining Social and Engineering Sources of Variation

Because each set of factors represent partially independent contributions to energy consumption, information about social variations between households may appropriately be included with information about architectural and technological variations in dwellings in the design of models of residential energy consumption. But these two sets of factors are, as we might reasonably expect, strongly correlated with one another, as well as with energy consumption. For example, in the U.S. dwelling size is clearly a "social class" phenomenon, with higher status households often occupying larger dwellings. Thus, we can "proxy" social variations with physical variations, because the latter are aspects of the "meaning" of the former; they literally "embody" social differences. But the reverse is also true. Measures of social member-

12 Our efforts to further specify the sources of this very high consumption at high income levels included estimating models which included terms interacting high income levels with the presence of air conditioning, and with the presence of air conditioning in inland climate zones. While high income households, with air conditioners living in hotter areas did consume more electricity, the sizes of the high income coefficients were effected very little by the addition of those interaction terms.

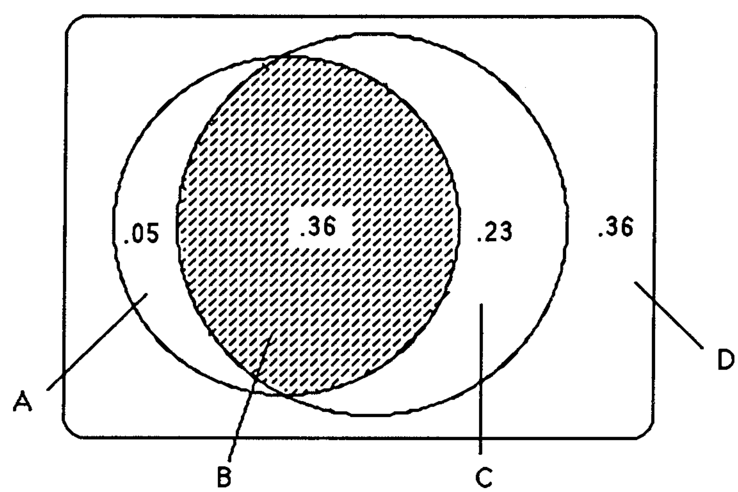
13 We have in mind both our own cross-cultural comparisons of electricity and gas consumption in California apartments (Hackett and Lutzenhiser, 1986;1988) and work by PG&E staff on the ethnicity variables included in the 1986 RASS survey (personal communication).

ship can also be used to represent architectural and technological differences between households.

In regard to the MIRACLE VI models, the R^2 for the socially-amended Electric Model is .643. If the CEC's engineering end-use variable set is entered first into the equation, it accounts for the bulk of this variation (.596). But if the socio-demographic variables are entered first, they account for .418 of the variance and the CEC variables only the remaining .225. When the joint and independent contributions of each variable set are calculated, the correlated social and engineering factors share .36 of the variance in consumption explained.

The two sets of variables are not perfectly correlated, because the social allocation of housing and appliances are historical processes, and are also subject, of course, to individual agency. For example, some access routes to housing opportunities are legally mandated, while others are constrained, so that we do not find a housing type for each type of culture, class, and stage in the life cycle. But social groups and their "appropriate" dwelling/technology ensembles coalesce in the formation of more or less stable and identifiable consumer lifestyle subgroups.

Figure 1. Sources of Variation in MIRACLE VI Residential Electricity Consumption (Proportion of Variance Explained - R^2)



A - Socially-variable behavior (technology-independent)
B - Socially-related building systems and appliances
C - Autonomous building system and appliance performance
D - Unexplained variation (specification error, unmeasured appliances micro-climate variation, ideosyncratic "tastes" and "preferences" unmeasured events, measurement error)

Figure 1 illustrates the independent and joint contributions of engineering and social variables (in the MIRACLE VI sample) to the explanation of residential energy use. It presents the outline of a theoretical model which distinguishes between: (A) socially-related behavior that is technologically independent (e.g. the conservatism of the elderly); (B) correlated social/technical consumption (e.g. the ownership of waterbeds by youths, conservation equipment by homeowners, or indeed the cultural preference of many groups for single family detached housing); (C) socially-independent physical system performance (e.g. the relationship of building envelope surface size to thermal transmission rates, regardless of housing type, age or condition); and (D) an unexplained residual composed of the effects of idiosyncratic behavior, measurement error and unspecified events.

The task which follows from this model is, of course, the sorting out of the connections between social groups and the architectural and technological features of their environments, whose interactions compose that large joint correlation with residential energy consumption. At bottom, the constituent groups of the society are its consuming units --not just their buildings and appliances-- and we need a better grasp of, for example, the shifting meanings of class membership, of the ways in which pools and hot tubs and larger homes come to serve (or cease to serve) as the markers of higher status living. The relationships between these groups and their technologies are fluid and poorly understood, making the task more difficult, but no less important. Utility data sets provide an important, and relatively untapped, resource for the sorts of studies needed.

Taking seriously the social or behavioral foundations of energy use also produces unexpected benefits. Comparing the empirical consumption patterns of groups (rather than "assuming" the "typical" consumption of individuals) directs our attention to the optional as opposed to necessary character of much energy consumption. Traditionally, "utilities" have been viewed as "necessary." But the great variation in observed "utilities" challenges this assumption. Indeed, some of our own recent research suggests that "demand" ought properly to be viewed as a secondary phenomenon, a product (not simply a source) of "supply," and often a relatively expendable one at that. One task of energy research, then, ought to be to disentangle the "reasonably required" from the "optional" —a distinction already made by utility planners sensitive to the issue of what can be cut in the event of curtailed supplies. And this amendment would make possible, in turn, a concern not simply with a single demand forecast, but with the development of alternative energy consumption scenarios, and tie forecasting more directly to the task of long-term energy planning.

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