A Comparison of Conditional Demand Estimates of Residential End-Use Load Shapes with Load Shapes Derived From End-Use Meters

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ABSTRACT

The purpose of this study is to compare alternative estimates of the average hourly loads for a set of residential appliances. Of particular interest in this study is the hourly contribution to consumption of air conditioning and refrigeration on the day of the system peak for a large utility. Such information is useful for demand-side planning.

The parameters of a combined thermodynamic and economic model of appliance usage are estimated using the conditional demand technique, a procedure invented by one of the current authors that is widely used for forecasting and conservation planning. Of particular interest in the current study is the opportunity to compare the conditional demand estimates of end-use load shapes with actual end-use metering.

In estimating the hourly end-use loads, the model takes into account factors such as household occupancy, income, weather, the size of the dwelling, energy prices, the presence of conservation devices. The thermodynamic model takes into account the effects of lights, people, and equipment as well as solar insolation and the effects of changes in outside air temperature. These factors are modeled as determinants of current energy consumption and heat storage, which can affect energy consumption in future hours.
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BACKGROUND

During a proceeding before the New York State Public Service
Commission (NYSPSC), an intervenor group attempted to demonstrate
that investments in end-use conservation measures should be made
in lieu of the completion of a nuclear power plant. The NYSPSC
found sufficient merit in the proposal to institute a generic
proceeding on May 7, 1982 (Case 28223) "to inquire into the
benefits to rate payers and utilities from implementation of end­
use conservation programs that will reduce electric use and of
the mechanisms, if any, that may be warranted to encourage
enthusiastic utility participation."

The NYSPSC (Opinion 84-15 -- May 21, 1984) concluded that
conservation should be considered as a means of satisfying
capacity needs in New York State and that utilities should
develop the expertise which would enable them to plan, evaluate,
and implement cost effective energy conservation measures. The
NYSPSC ordered utilities to submit annual compliance filings
describing plans to expand informational programs, conduct load
studies, develop management expertise in promoting conservation
programs, and to devise a uniform method for estimating marginal
revenues.

In compliance with the NYSPSC order an end-use load research
project to study the usage profiles of room AC and refrigerators
for directly-metered residential customers was undertaken by
Consolidated Edison Co.(ConEd). The specific purposes of this
load research project were: (1) to measure the contribution to
system hourly load of the residential class, (2) to measure the
components of this load resulting from the operation of room ACs
and refrigerators, particularly on the peak day, (3) to determine
the effect of substituting more energy efficient ACs and
refrigerators for those currently in place, and (4) to attempt to
develop a model for estimating end-use profiles based on total
load and demographic data without the need for end-use metering.
To comply with these requirements, ConEd and Applied
Econometrics, Inc. have performed a joint hourly conditional
demand study.
In this paper we will first provide a technical overview of the study. Following this we will discuss the salient theoretical engineering, and econometric issues underlying our analysis and then list and discuss our regression results. Finally we will summarize the study findings and offer an example of the way in which the model can be used to predict the hourly load implications of alternative conservation scenarios.

I. TECHNICAL OVERVIEW

As noted above, our analysis employs the Conditional Energy Demand (CED) technique which allows us to estimate appliance-specific energy usage and conservation effects without placing end-use meters on the appliances. The end-use metered consumption information has been used solely for comparison to the CED estimates of end-use load shapes. The study is based upon a 1986 data base containing the hourly consumption characteristics of ConEd residential customers. The data set contains: hourly whole-house and end-use consumption information, hourly temperature data; and very detailed information on household demographic variables, the building structural features and conservation measures. Using this data set and the CED technique we have been able to estimate an hourly load model for whole-house, AC, and refrigerator consumption that includes both engineering and economic relationships, and takes account of conservation, prices, weather, appliance holdings, the structural features of the residence, family economic characteristics, and the number of people home during the day.

The analysis is carried out using a sample of individual customer information and these results are then extrapolated to the ConEd system level. The analytical model we employ for this work is derived from combined economic and engineering theoretical relationships. Using this approach, the thermodynamic relations are used to specify the demand for energy for a particular appliance, given 1) its operating characteristics and environment and 2) the behavior of the occupants of the household. The economic theory is then used to model the behavior of the occupants as a function of variables such as prices and income. Once the model is specified in accordance with engineering and economic theory, the end-use energy demand equations are estimated using a modification of the original Parti-Parti Conditional Energy Demand technique [2]. Overall, the conditional demand estimation procedure has produced a detailed characterization of summertime hourly residential demand for the Coned service territory. The overall equation fit is good for conditional demand equations (the adjusted $R^2$ is .71) and the estimated regression coefficients are within reasonable ranges.

10.205
II. THEORETICAL ISSUES

In this section we present a brief summary of the conditional energy demand (CED) technique and then discuss the engineering models for the AC and refrigerator load shapes. Then we discuss our use of an appliance stock variable and the overall CED equation structure.

II.A. A Summary of the Conditional Energy Demand Technique

The CED technique employed in this study is used to disaggregate the customer load into its end-use components. The conditional demand technique carries out the disaggregation of the customer load into its end-use components by applying multiple regression analysis to a data set composed of customer-level load data, survey and weather information. The technique is based upon an equation form that is derived from three ideas: 1. the load measured at the customer-level meter is the sum of the loads of the appliances connected to the meter; 2) if an appliance is not connected to the meter, it contributes no load to the meter; and 3) appliance loads vary across customers. The mathematical form generated from this orientation is presented in reference [7].

III.B. Engineering Models for Air Conditioning and Refrigeration

The CED equation we estimate consists of component demand equations for particular end uses. The end-use categories of particular interest are the room AC and the refrigerator. We base our estimation procedure for them on an underlying engineering model. Further, the AC engineering model is linked to an economic/behavioral model which characterizes consumer reactions to changes in prices and income as well as lifestyle patterns. The AC model explicitly considers weather (insulation, dry bulb, temperature, humidity); building configuration (number of floors, percentage of window surface, etc.); floor area; and occupant behavior (thermostat settings, changes in infiltration levels, etc.). We model the inside temperature and thermostat setting so that logical occupant behaviors are implemented within the model.

We embed a difference equation similar to those used in building simulations in the regression process. This procedure is a feasible approach to integrating engineering and economics and has a number of major benefits over conventional methods: 1. It precludes a bias in the engineering portion of the estimation process between the average days and peak load days. There is only one model of the building which responds correctly in periods of both high system load and constantly available weather patterns. This is possible because we are actually capturing the
thermodynamically correct structure driving the buildings. 2. Weather normalization is automatically done correctly since weather enters in the thermodynamically correct way. 3. It permits use of conditional demand techniques to consider the appliance stock and conservation devices. 4. It permits incorporation of rational consumer behavior during unoccupied periods. This permits generation of a single model in which different portions of the day are subject to normal thermodynamic effects but exhibit specific behavioral differences. 5. It results in a difference equation useful for driving the variables of interest in system planning. 6. It lends itself to aggregation and comparison with system level consumption data. 7. It provides a tremendous degree of meaningful data compression. The processes generating the actual data closely follow the proposed difference equations, and therefore we are compressing data in precisely the optimal manner.

THE APPROACH

The approach is best understood by reference to three modules: 1) the difference equation for temperature; 2) the building's AC load at a given time; and, 3) the economic model for behavioral variables. We first summarize these modules formally in turn and then show how they are specifically implemented in our conditional demand regression equation.

Module 1 - The difference equation for temperature: Dynamic heat transfer in buildings is closely approximated by a difference equation of the form:

\[(\text{III.B.1a}) \quad X_{k+1} = A_k X_k - B_{1k} e_k(a/c) + B_{2k} e_k(\text{non a/c}); \text{ and} \]
\[(\text{III.B.1b}) \quad T_{k+1}(\text{in}) = C_{k+1} X_{k+1}; \]

where \(k\) refers to the \(k\)th time interval; \(X_k\) is a vector of internal building thermal mass temperatures at the \(k\)th time interval; \(A_k\) is a matrix whose elements depend on physical characteristics of the building (e.g. size, window area, insulation levels, infiltration levels etc.); \(e_k(a/c)\) is the energy consumed by the building AC at time step \(k\); \(e_k(\text{non a/c})\) is a vector containing all other energy inputs, (e.g. weather) into the building at time \(k\); \(B_{1k}\) and \(B_{2k}\) are matrices of coefficients, derived from engineering analysis, depending on physical characteristics of the building; \(T_{k}(\text{in})\) is the building's internal air temperature at time \(k\); \(C_k\) is a vector of engineering coefficients dependent on the physical description of the building. The elements of these equations are discussed in detail by Sebald et. al. in References 8 and 9.
This structure permits approximation of the building's interior temperature at time k, given only the matrices A, B and C as well as measured weather data and hourly appliance consumption. This means that only the coefficient matrices need be determined to completely specify the interior temperature at any hour of any day. Only a small fraction of the components of these matrices need to be estimated given available engineering theory.

Eqn (III.B.1) requires an initial condition to start a day's forecast. We find that load shapes during a 24 hour period are relatively insensitive to plausible variations in initial conditions 12 hours before the first hour to be modeled.

**Module 2 - The building's AC load during a given time step:** Given the temperature module, the estimated hourly cooling load at time k would equate $T_{k+1}$ to the thermostat setting at time $k+1$. Solving for the air-conditioning load we obtain:

$$\text{(III.B.2)} \quad e_k(a/c) = \{C_{k+1}A_kx_k + C_{k+1}B_{1k}e_k(\text{non a/c}) - \text{Thermostat}_{k+1}\} [C_{k+1}B_{1k}]^{-1}.$$

However, actual $e_k(a/c)$ is zero if the interior temperature is below the thermostat setting; and, it cannot exceed the capacity of the AC. Equation (III.B.2) and the above considerations generate a second control module.

Equation III.B.1 naturally deals with zones. In a multizone model, T is a vector of zone temperatures; $e_k(a/c)$ is a vector and the thermostat setting in eqn III.B.2 will also be a vector of zone thermostat settings. Practically, however, appropriate temperature zone data (obtained from reading or models) are required. We attempted to model alternative single and multizone constructs and obtained better explanatory power with the single zone model. This may be because the room air-conditioners were generally used alone or in tandem to cool the whole house rather than one room.

Hourly schedules for AC also naturally fit in the above model. Eqn. (III.B.2) can easily be constrained by measured hourly schedules. Such data were available in this study, but ConEd wanted a more generally applicable model, one based only on summary house data.

Finally, latent load is included in a separate submodule. The structure permits arbitrarily complex latent load models. However, in the current study a simple average latent load model based on ASHRAE and summary humidity data was used. It is crucial to recall that the overall model was calibrated...
statistically. We did not impose results from a theoretical model.

Module 3 - The Economic Model: Modules 1 and 2 contain various behavioral variables: thermostat setting, etc. These variables cannot be modeled with engineering theory. Typically, one views these consumer decisions as utility maximization subject to a budget constraint. In some settings this results in behavioral decisions based on the ratio of an adjusted income measure to the price of energy. In this study, decisions about thermostat settings were modeled using the above income/price ratio. One also must include the thermal integrity of the building since the price of lowering the building temperature one degree depends on both the energy price and the thermal integrity. These relationships comprise module 3.

Combining Modules 1, 2 and 3, we obtain a building model which is driven by survey data on the building and its occupants, prices, weather, and consumption (see Figure 1). Output of the model is an hourly value of AC load computed from the wattage (kw) drawn by the AC and its percent on time. It is important to note that this is a truly integrated model, in that the entire model is simultaneously imbedded in the regression process in order to calibrate the results against measured data in one estimation step.

The Overall Model:

This overall scheme is implemented in the current model by calling the engineering model as a subroutine in our regression procedure. The subroutine produces an estimate of the AC energy used during an hour based on the thermostat setting, structural features of the house, equipment efficiency and conservation hardware, the outside temperature, estimates of internal gains due to occupants, lights and equipment and solar radiation at each hour, and estimated heat storage effects. The subroutine produces an estimate of AC usage for each household-hour in our sample. These estimates are included in our regression equation as explanatory variables. The thermostat setting comprises two parts, a 75°F reference temperature and the change from that reference provided by the economic model in response to prices, etc. as described above. Note that the economic model also is driven by the quantity of energy predicted by the engineering subroutine.

The refrigerator model is similar in concept though much simpler in execution. Refrigerator heat loss is correlated with unit capacity by use of a box geometry model for the area of the refrigerator. The box area depends on capacity subject to aspect ratio constraints. U values, infiltration and content heat

10.209
capacity were not explicitly modeled. The engineering subroutine yields estimates of refrigerator consumption that depend upon capacity and whether it is frostfree. We have excluded price and income terms for the refrigerator in our model because there was no measurable effect for these variables for the refrigerator in our regressions.

III.C. Use of the Appliance Stock Variable

This study is primarily concerned with the whole house load and with the refrigeration and AC end-uses. In addition, we take account of information about other appliance categories using a summary measure we call an appliance stock variable. This variable is a weighted sum of the following appliance category variables: number of black and white and color tv sets, vcr, personal computer, water bed, dishwasher, freezer and an unspecified category. The weights for these appliance variables are hourly btu end-use consumption estimates derived from engineering and conditional demand studies. This variable is used directly in the regression equation and as an input into the heat gain component of the engineering model determining AC. See Reference 6 for a detailed discussion of the use of the appliance stock term.

III.D. Overall equation structure

In the estimating equation the hourly residential load, \( E_h \), is written as the sum of the hourly end-use demand functions for room AC, \( e_{RoomAC_h} \), frostfree refrigerators, \( e_{FFh} \), nonfrostfree refrigerators, \( e_{NFh} \), pool pumps, \( e_{Poolh} \) central AC, \( e_{CentAC_h} \) and an unspecified category, \( Unspecified_h \), at hour \( h \) as follows. (See III.A.1)

\[
(III.D.1) \quad E_h = e_{RoomAC_h} + e_{FFh} + e_{NFh} + e_{Poolh} + e_{CentAC_h} + Unspecified_h
\]

IV. EMPIRICAL RESULTS

The sample consisted of 16,131 observations on the peak day and a randomly selected day during the same summer season. The analysis was restricted to a 24 hour period beginning at 1 A.M. There were, however, 12 hours of the previous day's data included in our analysis as part of our computations of the heat storage trajectory for the AC model. The model breaks down the hours of the day into four general hourly categories which are used to define incremental category variables in our model.

<table>
<thead>
<tr>
<th>Time Period: NIGHT</th>
<th>MORNING</th>
<th>MIDDAY</th>
<th>EVENING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time:</td>
<td>12AM-6AM</td>
<td>7AM-9AM</td>
<td>10AM-5PM</td>
</tr>
</tbody>
</table>

The hours listed refer to consumption in the hour ending at the indicated time. Consumption for each hour can vary within
each of these categories in response to variations in the weather, etc. Accounting for these hourly differences in the coefficients is useful since it allows for different responses to weather changes, etc. when people may be generally home rather than away.

The data set consists of pooled cross-section/time-series observations and the underlying error structure modeled in connection with the conditional demand equation is heteroskedastic with cross-sectional variations in the error variance associated with appliance stock differences combined with first-order serial correlation. We address the heteroskedasticity issue by modeling the error term as a function of the appliance stock as in reference 6. The first-order serial correlation issue is addressed in several stages by estimating a serial correlation coefficient separately for each household and using this to create a generalized difference form of each variable as outlined in references 4 and 5. These transformations are applied simultaneously to each observation. Although the error structure is modeled in several stages, the general strategy is to estimate an overall hourly energy use equation in a single final stage.

The conditional demand regression model estimated in this study can be used as the basis for a microsimulation model to predict changes in load shapes that result from conservation, appliance saturation changes, changes in weather, prices and demographics. Using our estimated model we calculate a set of predicted load shapes. In figures 2 and 3 we compare the actual and predicted values of hourly whole house and room AC consumption for the peak day. Similar graphs are available for refrigerators. In table 1 we present the regression results for the estimated conditional demand equation. Table 2 contains the definitions of the variables. The goodness of fit characteristics of the conditional demand model are very good as shown by the $R^2$ and t-ratios. The model does very well at predicting average behavior.

Examining the ACLOAD coefficients for room AC, we see that they are less than 1. This means that the engineering estimates of the load generally overpredict. This is understandable since the engineering model uses the entire space of the house rather than the portion apparently served by the individual ACs. We chose this approach because using the areas of the rooms served by the ACs led to poorer estimates. It may be that room ACs are used to cool more than one room.

As regards the central AC, the MIDDAY and EVENING estimates are close to unity. Thus for these periods the engineering model is very accurate in predicting energy usage through the central AC. The relatively small coefficients for the other periods,
however, indicate that the engineering estimates for these periods are too high.

Calculation of estimated AC consumption for a given hour involves combining relevant terms in Table 1. For example, consumption for a room AC in a given hour is the sum of its ACLOAD, plus its ACLOAD for JULY (if the relevant month is July), plus its component of GENERAL IncPriceRoom, plus its component of EVENING IncPriceRoom (if the hour is during evening). Each of the above components comprises the product of the coefficient in Table 1 and the corresponding explanatory variable from the engineering or economic subroutines.

As described above, the frostfree and nonfrostfree refrigerator variables are constructed in such a way that the refrigerator heat loss varies with increases in the capacity of the unit. The model does not attempt to account for all the hour-to-hour variations in refrigerator usage, since they are quite small, but it has been used to test for differences across the general time periods used in our analysis. The pool pump coefficient summarizes the average pool usage during an average hour (in btu's).

In the unspecified model, the STOCK and OCCUPANTS terms were included except when their t-ratios were very small (in this case less than .5) in absolute value. Since all of the non Intercept variables in this category are multiplied by the STOCK variable, the negative sign for that variable in the NIGHT and EVENING periods do not mean that negative unspecified consumption would occur during those periods. The OWNHOME variable is significant.

The income/price coefficients are defined separately for the mutually exclusive cases of customers who have room AC and customers who do not have room ACs. A positive coefficient for these variables means that the load rises with increases in income and declines with increases in the price of electricity. Other things equal, the greatest income/price sensitivity occurs during the EVENING period when the occupants are home and active. To compute the overall price elasticity (−.13) we used a microsimulation approach, increasing the peak day price by one percent and computing the average percentage decline in consumption across all the hours of the day.

V. Summary and Conclusions

The purpose of this study is to model end-use hourly residential load shapes based on demographic and total load profiles. Of particular interest in this study is the whole house, the room AC and the refrigerator categories. The roles of conservation devices and appliance efficiencies are of particular interest. In estimating the hourly end-use loads, the model
takes into account factors such as household occupancy, income, weather, dwelling size, energy prices, appliance efficiency, the conservation devices and the appliance stock.

The estimation procedure employs a statistical technique, conditional demand analysis, along with survey, weather, and hourly load data, to yield an equation that relates hourly consumption to the previously named factors. Once the equation is estimated, the hourly household-level load can be broken into its end-use components. For example, to compute the frost-free refrigerator load for a morning hour in a house that contains one 19 cubic foot frost-free refrigerator, we would multiply the GENERAL coefficient for the frost-free refrigerator, 16.4271, by the value of the FLOAD variable generated by our engineering model, 42.8, to obtain the number of btu's. Dividing this number by 3413 (the number of btu's per kwh) we obtain an estimate of

The overall results of the study are quite good in a goodness-of-fit sense, particularly as regards the model's ability to predict average hourly loads. In addition, the findings of the analysis indicate interesting differences across the hours of the day in price, income, weather and occupancy effects as well as usage differences across the hours.

The findings can be used directly as in the case of the different price sensitivities across time periods and room AC ownership groups. If our end-use equations are imbedded in a planning model they can be used to simulate the effects of alternative rate and demand management strategies. If we postulate a program that yields a general increase of slightly over 11% in the efficiency of all the room AC, the resulting decline in the average hourly whole house load for residences is calculated by the model as shown in figure 4. The model can also be used to compute changes in whole house loads that result from more complicated hypotheses in which prices, weather, appliance efficiencies and saturations change simultaneously. This last property of the model is designed to aid ConEd in complying with the NYSPSC order to plan cost-effective conservation measures.

References


Figure 1
The integrated engineering and economic model
Figure 2
Estimated and Actual Hourly Whole-House consumption (kwh) for the Peak Day. All Data are Averaged Over the Sample.

Figure 3
Estimated and Actual Hourly Per-Unit Room Air Conditioner Consumption (kwh) for the Peak Day. All Data are Averaged Over the Sample.

Figure 4
Estimated Hourly Effects of Air Conditioning Efficiency Changes on Whole House Consumption. Consumption is in kwh. All Data are Averaged in the Sample.
Table 1
The Hourly Conditional Demand Equation

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>STAND ERR</th>
<th>t-RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOM AC:</td>
<td>ACLOAD</td>
<td>0.2913</td>
<td>0.0202</td>
<td>4.5125</td>
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<td></td>
<td>ACLOADeer</td>
<td>0.6333</td>
<td>0.4276</td>
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<td>ACLOAD</td>
<td>0.0734</td>
<td>0.0192</td>
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<td>ACLOADeer</td>
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<td>UNSPEC.: GENERAL</td>
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<td></td>
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<td>0.2136</td>
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<td>IncPriceRoom</td>
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</tr>
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<td>378.8931</td>
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<td>-0.3359</td>
<td>0.1496</td>
<td>-2.2451</td>
</tr>
</tbody>
</table>
OCCUPANTS STOCK JULY OCCUPANTS
0.1954 0.0575 3.3993
-1.7184 0.5592 -3.0731
0.2126 0.0386 5.5068

Table 2
Definitions

ROOM AC ..... the room air conditioner category
MIDDAY ..... the MIDDAY category defined above
ACLOADeer ... engineering estimate of air conditioning
weighted by the eer
ACLOAD ...... The engineering estimate of air conditioning
EVENING ..... the EVENING category defined above
MORNING ..... the MORNING category defined above
NIGHT ....... the NIGHT category defined above
JULY ......... the month of July category
CENTRAL AC .. the central air conditioning category
REFRIGERATOR the refrigerator category
FROSTFREE ... the frost free refrigerator category
FFLOAD ...... an estimate of the average surface area of
the frostfree refrigerator.
NONFROSTFREE the nonfrostfree refrigerator category
NFLOAD ...... an estimate of the average surface area of
non-frost-free refrigerators.
POOL PUMP ... the pool pump category
Intercept ... a constant term for the appliance category
in which it occurs
UNSPECIFIED the unspecified appliance category
STOCK ....... the appliance stock variable described in
section III
OCCUPANTS ... the number of household occupants multiplied by the
STOCK variable except during the MIDDAY period,
when OCCUPANTS is the number of people home during
the day multiplied by the STOCK variable.
OWNHOME .... a home or apartment ownership indicator variable (1
= YES, 0 = NO) multiplied by the STOCK variable.
IncPrice ... the STOCK variable multiplied by normalized
household income (household income divided by its
mean) divided by the normalized marginal price of
electricity. This variable is calculated for
households with no room air conditioners
IncPriceRoom the IncPrice variable for households with room air
conditioners.

10.218