# QUANTIFICATION OF RESIDENTIAL BEHAVIORAL PATTERNS WITH INTEGRATED THERMODYNAMIC/ECONOMETRIC MODELING

M. Parti, Applied Econometrics Incorporated,
A V. Sebald, University of California, San Diego, and
E. Y. Won, Southern California Gas Co.

## ABSTRACT

This paper applies Thermodynamic Behavioral Integration (TBI) modeling to natural gas consumption in the residential sector in the Southern California Gas(SOCAL) area (Los Angeles CA). TBI uses conditional demand techniques to integrate thermodynamic and behavioral models. A crucial aspect of the integrated model is explicit incorporation of feedbacks between the engineering and economic components. For example, consumer choice of thermostat setting is affected by the price of raising the interior temperature by a degree, which in turn, depends on the thermal tightness of the house. Overall price and income elasticities are computed. The perverse price effect (conservation tends to make warmth cheaper and therefore tends to increase consumption) is naturally included in this structure. This technique has been applied to modeling residential electric consumption, commercial electric consumption, and industrial gas consumption with excellent results.

The paper discusses a recent study of residential gas consumption in the SOCAL Gas service territory. Special emphasis was placed on use of TBI to quantify behavioral patterns including level of use variables and estimated relations between claimed and actual use of appliances. It also estimated the load effects of building and appliance vintage differences. The study included 5 end uses: space heating, water heating, cooking, clothes drying and pool heaters. Results of the study include unit energy consumption for each appliance, price elasticities by end use, estimates of load effects of customer demographic and life style characteristics, estimates of load effects of building and appliance vintage differences, and estimates of the actual behavior of customers in determining the comfort/convenience (i.e. utility) of the services provided by natural gas usage.

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## I. INTRODUCTION

This paper discusses a technique to increase the accuracy with which behavioral aspects of residential energy consumption can be statistically measured. The principal focus here is twofold: (i) price and income elasticities of energy use in the residential sector and (ii) demographic and other factors that explain energy consumption and conservation behavior. We believe that these problems are strongly coupled and should be analyzed in an integrated framework which explicitly contains, in their proper places, simultaneously interacting models consistent with engineering, economic and behavioral theory. The Thermodynamic Behavioral Integration (TBI) approach, based on conditional demand techniques, provides an appropriate framework for this.

## II. THE APPROACH

Economic, engineering and behavioral theory all are valuable in studies such as this. Used separately, each has well-known and serious disadvantages. Engineering theory relies heavily on detailed descriptions of the building in question and its usage patterns. Real study data sets typically do not have sufficient detail especially in the latter area. Economic and behavior theory give rational prescriptions for modelling occupant behavior but gives no assurance that the overall model structure is faithful to the laws of thermodynamics. These obviously complementary approaches can be combined in order to substantially improve estimation performance.

### The Thermodynamic Behavioral Integration Model

We have adopted a modeling strategy like that depicted in Figure 1. There are three types of data (physical, economic and behavioral) and there are two types of sub-models (engineering and economic/behavioral). We begin with a thermodynamic description of the way in which energy is consumed in each of the desired end uses. Consumer decision variables naturally appear in such an analysis. Using economic and behavioral theory, a model is then generated for all of the decision variables in the engineering model. In general, economic decisions in residences will depend on variables such as prices, income,

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[1] This study was funded by Southern California Gas Co. The Company, however, should not be held responsible for any of the conclusions.

[2] Dr. Won did not have an opportunity to review the final version.

lifestyle variables such as age and family composition of the occupants and even certain thermodynamic variables.

The result is a coupled set of engineering and decision models driven by the data set. Various approaches can be used to parameterize the models for estimation purposes and the number of parameters to be estimated is not excessive. At this stage, we have a theoretical model which, if correct, would perfectly predict the energy consumption of each building in the data set.

IT IS CRUCIAL THAT THE MODELS OF FIGURE 1 BE VIEWED AS SIMULTANEOUSLY FEEDING EACH OTHER. THEY ARE FULLY INTEGRATED SIMULTANEOUS MODELS.

Both the engineering and behavior models contain parameters which are not perfectly known. The combined model must therefore be calibrated as depicted in Figure 2. The calibration procedure adjusts these coefficients and also quantifies whether the entire integrated model structure is appropriate. IT IS CRUCIAL THAT THE ENTIRE INTEGRATED MODEL BE SIMULTANEOUSLY ADJUSTED IN A SINGLE ECONOMETRIC PROCEDURE. It is not sufficient to fix the engineering model and adjust its output with a price term. We are proposing a completely integrated calibration in which the individual end use components can be individually calibrated by the regression.

This method has been successfully used in residential, commercial and industrial studies [2..5]. The work described here builds on these results by enhancing the behavioral model.

## III THE STUDY SPECIFICATION

This paper adresses residential natural gas consumption patterns in the service territory of SoCal Gas Co. (Los Angeles CA). The study has three goals: 1)Forecasting of residential gas consumption in the face of changes in physical description of houses, prices and lifestyle variables affecting occupant behavior; 2) Explicit consideration of conservation devices and practices; and 3) Explicit consideration of variables which affect occupant behavior as it relates to energy consumption. Six[3] end uses were modelled, each affected by relevant conservation devices[4]. Weather is given in Table I.

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[3] space heater, water heater, pool heater, clothes dryer, range, and unspecified

[4] Solar space heater, Solar water heater, Solar pool heater, Pilot light turned off in summer, Electronic ignition pilot light, Fireplace damper closed, Attic insulation, Attic insulation R-value, Wall insulation, Caulking/Weather stripping, Duct insulation, Water heater blanket, Flow control showerheads, Pool Cover, Portion of year pool cover is on.

Table I: Weather (Heating Degree Days) During the Study Period as Compared with an Average Year[5]

| | March 1984-<br>Feb. 1985 | Average Year |
|---|---|---|
| Heating season (Nov. - May) | 1327 | 1389 |
| Nonheating season (June - Oct.) | 34 | 59 |
| Annual cycle | 1361 | 1448 |

## IV STEP I: AN EXPLORATORY CONDITIONAL DEMAND MODEL

### An Overview

We begin by defining, for each end use, an engineering model for consumption in a given building. At this stage, decision variables like hot water consumption and thermostat setting are easily placed correctly in the structure, but their precise value must be obtained from claimed behavior (from the survey) or assumed. In steps II and III, such variables under consumer control will be modeled using demand theory from economics and behavior theory.

### Details of the Proposed Engineering Model

The basic model will explicitly account for differences in average appliance efficiency over both time and locality, weather dependence and conservation devices. We begin with an accounting identity. A combined gas and electric model could also be used.

$$\begin{aligned} GAS_{MONTH} = {} & GAS_{SPACE\ HEAT} + GAS_{WATER\ HEAT} \\ & + GAS_{COOKING} + GAS_{UNSPECIFIED}. \end{aligned} \tag{1}$$

IT IS CRUCIAL THAT INTERACTIONS AMONG TERMS BE PROPERLY CONSIDERED. Space heating is affected by internally generated heat:

$$\begin{aligned} GAS_{SPACE\ HEAT} = (EFF_{SH})^{-1} * \{ & \text{HEAT LOSS} \\ & - \text{gain from sun} - \text{gain from lights} \\ & - \text{gain from people} \\ & - \text{gain from equipment}\}; \end{aligned} \tag{2}$$

where gains from lights and equipment are functions of the relevant electricity terms. Such feedbacks are a natural result of the engineering perspective.

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[5] Thus, observed gas use over this period and for the heating and nonheating seasons within it should closely approximate weather-normalized gas use.

### effects of conservation

Each of the terms in Equation (1) is affected by conservation devices/practices. Increased precision and the ability to measure actual impacts can be achieved if conservation effects are imbedded in the basic end use models.

Using space heat as an example,

$$GAS_{SPACE\ HEAT} = \underset{i}{\text{sum}} \{BASE_{SPACE\ HEAT,i} * \underset{j}{\text{product}}(1 - k_{ij} * D_j)\}, \qquad (3)$$

where

$BASE_{SPACE\ HEAT,i}$ is the base load associated with component i (e.g. the ceiling) absent conservation,

$k_{ij}$ = proportionate savings on $BASE_{SPACEHEAT,i}$ due to device j, and

$D_j$ = 1 if conservation device j is installed and 0 if not.

Efficiency changes can be tested by making EFF in (2) a function of appliance mixes resulting from tighter standards. One can rewrite Equation (3) to include both a base term as defined above and a savings term:

$$GAS_{SPACE\ HEAT} = BASE_{SPACE\ HEAT} - SAVINGS_{SPACE\ HEAT}, \qquad (4)$$

Note that the function $BASE_i$ is specified by engineering analysis and can be calibrated econometrically.

### Summary Equations

The following end use summary equations were used in the analysis. Consumer decision variables are underlined and the list of primitive variables on which each term depends is given in parentheses. Decision variables are defined in Table II.

### Space Heat

$$\begin{aligned} GSH = \{&UA'_{shell}(EFF^{-1}_{sh}(\text{furnace vint./type}), \text{physical characteristics of bldg}) \\ &+ UA'_{infil}(EFF^{-1}_{sh}(\text{furnace vintage/type}), \text{tightness of bldg}) \\ &[1-k_{wstrip}\ \underline{D}_{wstrip}]\} * \underline{D}^* \\ &- HEATGAIN(E^{-1}_{sh}(\text{furnace vintage/type}), SUN, \text{Bldg contents}) \\ &+ PILOT'_{sh}(PILOT_{sh}, D_{iid,sh}) * (1-\underline{D}_{poff}). \end{aligned} \qquad (5)$$

where

| | |
|---|---|
| $UA'_{shell}$ | is the overall efficiency weighted area conductance term for the shell, |
| $UA'_{infil}$ | is the overall efficiency weighted area conductance term for infiltration, |
| HEATGAIN | is the efficiency weighted integral of the effects of SUN and other internal heat gains, |
| $PILOT'_{sh}$ | is the monthly pilot light load, |

Water Heat

$$\begin{aligned} GWH = {} & \text{Int}\,\{UA'_{wh}(E^{-1}_{wh}(\text{vintage of wh,Solar}),\ \text{heater const, conserv dev}) \\ & \quad * (T_w - T_{a,wh})\}\,dt \\ & + c_p * \{\underline{W^*}_{dish} * [1+k_{ADW}\,ADW] + \underline{W^*}_{cloth} * CW + \underline{W^*}_{bath} \\ & + \underline{W^*}_{shower} * [1-k_{flo}\,\underline{D}_{flo}] + W^*_{other}\} + PILOT'_{wh}(PILOT_{wh}), \end{aligned} \tag{6}$$

where

| | |
|---|---|
| GWH | is the consumption of natural gas for water heating during the period of interest (e.g. a month). |
| Int | indicates integration, |
| $E^{-1}_{wh}$ | is the recovery efficiency of the water heater, |
| $T_w$ | is the water temperature inside the water heater, |
| $T_{a,wh}$ | is the temperature of the air surrounding the water heater, |
| $c_p$ | is the number of BTU's required to heat a gallon of water one degree F, |
| CW | is a binary variable indicating ownership of a clothes washer in the home, |
| $k_{flo}$ | is the proportionate savings due to the shower flow restrictor, |
| $PILOT_{wh}$ | is the water heater's pilot light load during the period of interest. |

Clothes Drying

$$GDY = q * \underline{(FACTOR * LOADS)} + PILOT'_{dry}(PILOT_{dry}, D_{iid,dry}), \tag{7}$$

where

| | |
|---|---|
| q | = 3 kBtu/load is the number of BTU's required to dry one load of clothes, and |
| $PILOT'_{dry}$ | is the pilot light load for the period. |

## Cooking

$$GCK = PRT * \underline{HRS}_{top} * [1-\underline{k}_{micro,top} D_{micro}]$$
$$+ POV(EFF^{-1}_{oven}, UA_{oven}, T_{cook}, T_{inside}) * \underline{HRS}_{oven} * [1-\underline{k}_{micro,oven} D_{micro}]$$
$$+ PILOT'_{ck}(PILOT_{top}, D_{lid,top}, PILOT_{oven}, D_{lid,oven}), \qquad (8)$$

where

| | |
|---|---|
| $PRT$ | is the average gas power consumed by the range top in a month (Btu/hr), |
| $D_{micro}$ | is a binary variable indicating ownership of a microwave oven. |
| $POV$ | is the gas power consumed by the gas oven (Btu/hr), |
| $PILOT'_{ck}$ | is the total pilot load for cooking during the month. |

## Pool Heating

$$GPH = RCE_{ph}(E^{-1}_{ph}(\text{heater vintage}, k_{psol}, D_{psol}), T_p, \text{weather}) * [1-k_{cov} \underline{D}_{cov}]$$
$$* SBR_{ph}(E^{-1}_{ph}(\text{heater vintage}), \underline{T}_p, c_p)$$
$$+ PILOT'_{pool}. \qquad (9)$$

where

| | |
|---|---|
| $RCE_{ph}$ | is the total monthly load due to radiation, convection and evaporation, |
| $k_{cov}$ | is the proportionate savings in radiation and convection due to a pool cover, |
| $T_p$ | is the temperature of the pool water, |
| $SBR_{ph}$ | is the efficiency weighted standby loss plus the replacement water heating load, |
| $PILOT'_{pool}$ | is the monthly pilot load for the pool heater. |

## Unspecified

In addition to all the above specified end uses, gas might be consumed in a variety of other end uses. Adopting the traditional conditional demand perspective, we classify such end use consumption as unspecified. The unspecified consumption cannot, by its nature, be modeled in a detailed engineering framework. However, the unspecified model will be constructed so that it is consistent with the utility maximization model to be employed in deriving gas demand equations for the specified end uses. Thus, unspecified consumption, GMISC, will be viewed as a function of prices, income and other household characteristics and will be treated as a decision variable.

A summary of the model's decision variables is given in Table II.

Table II: Decision Variable Summary

| Variable | Purpose/Definition |
|---|---|
| SPACE HEATING | |
| $D_{poff}$ | = 1 if pilot off during summer, 0 otherwise, |
| $D_{wstrip}$ | = 1 if weatherstripping installed, 0 otherwise, |
| $D^*$ | = integral of $\{T_{out} - T_{in}$ if $T_{out} < T_{in}$, 0 elsewhere$\}$. |
| WATER HEATING | |
| $W^*_{dish}$ | hot water used for dishes in the home, |
| $W^*_{cloth}$ | hot water used for clothes washing in the home, |
| $W^*_{bath}$ | hot water used for baths in the home, |
| $W^*_{shower}$ | hot water used for showers in the home, |
| $D_{flo}$ | = 1 if shower flow restrictors installed, 0 otherwise, |
| CLOTHES DRYING | |
| (LOADS*FACTOR) | is the number of loads of clothing multiplied by the propensity to over-dry clothes, |
| COOKING | |
| $HRS_i$ | = number of hours i is used in the absence of a microwave oven (may be a function of N) (i = top,oven), |
| $k_{micro,i}$ | is the proportionate reduction in meals cooked on i due to the presence of a microwave oven (i = top, oven), |
| POOL HEATING | |
| $T_p$ | pool temperature, |
| $D_{cov}$ | = 1 if pool cover installed, 0 otherwise, |
| MISCELLANEOUS | |
| GMISC | gas usage through the miscellaneous appliances |

## V STEP II: INTRODUCTION OF ECONOMIC THEORY

This section derives demand equations for the consumer decision variables identified above. Here, the decision variables are modeled as functions of fuel price, income and selected thermodynamic variables. The approach is to postulate a utility function which will be minimized subject to a budget constraint. The process results in optimal functions governing the decision variables in each end use. The functions then replace the assumed decision variable values from step I. The result is a combined engineering and economic model which yields calibrated price/income elasticities for each end use. Note that the values of the decision variables now vary with price, income, thermal integrity and weather across the data set.

### Utility Functions

Consider a utility function, U, as follows:

$$U = U(d_1, \ldots, d_D \; ; \; H_1, \ldots, H_L) \qquad (10)$$

where $d_i$ represents the value of the i'th decision variable; and,
$H_k$ represents the value of the k'th lifestyle indicator variable for the household.

The budget constraint is:

$$Y = Pg * [\ GSH + GWH + GCK + GDY + GPH + GMISC]$$
$$+ Pc * [CONSERVATION] + Po * [\ OTHER\ ]; \qquad (11)$$

where Y is monthly income,
Pg is the price of gas.
Pc is a price vector for conservation measure implementations,
Po is a price vector of other goods,
CONSERVATION is a vector of conservation measure implementations,
OTHER is the quantity of other goods consumed in a month,
GMISC is the gas consumption in the miscellaneous category in a month,

and all the other variables are defined as above.

To convert Equation (11) into a form dependent on the decision variables, discretionary components of consumption are hypothesized for each of the end-use categories, and the magnitudes of the components are determined by a set of consumer decision variables. The optimal values of these decision variables are obtained, as noted, in a utility optimization framework.

### V.1 The Revised Budget Constraint and Implicit Prices

A new budget constraint can be written to reflect the expenditures on each decision variable in Table 5. This new budget constraint is equivalent to the old budget constraint; however, it explicitly takes into account the marginal price effects of changing the endogenous decision variables:

$$\begin{aligned} Y=\underset{i}{\text{SUM}}\ \{&\underset{j}{\text{SUM}}[(\text{Implicit Price of Decision Variable})_{ij} \\ &\quad *(\text{Decision Variable})_j\ ] * A_i\} \\ +\ \underset{i}{\text{SUM}}\ &[(\text{Price of Gas}) * (\text{Non-Discretionary Level of Gas Use})_i * A_i] \\ &\quad + P_c\ \text{CONSERVATION} + Po * \text{OTHER}; \end{aligned} \tag{12}$$

where $j$ is the index of the endogenous decision variables,
$i$ is an the index of appliances, and
$A_i$ = 1 if appliance $i$ is present, 0 otherwise.

### Implicit Prices

We define the implicit price as the marginal cost of changing the endogenous decision variables given the price of gas and the physical characteristics of the gas appliance and, for some appliances, the structure of the building. Substituting the implicit prices, decision variables, non-discretionary levels of gas use, conservation measures, and other expense items associated with each end use in Equation (12) yields the final budget constraint.

### The Effect of Price

We have grouped the end-use appliances into four preliminary price response groups for convenience. The first group (space and water heaters) contains appliances that are used to satisfy important daily needs of the household and for which there are no very good alternatives. Although the non-discretionary portion of these loads may be large, it is apparent from previous studies that an important component of these loads can be affected by price. The saturations of these appliances for the single-family residences are very high.

The second group (pool heaters) contain appliances with dominant discretionary loads. This group is characterized by relatively small saturation. In general, we would expect the price elasticities to be higher in this group than in the first common elasticity group.

As in the case of the first appliance group, the third group of appliances (range and dryer) is used to satisfy important daily household needs for which there are no good (at home) alternatives. However, unlike the first group, the expected gas consumption for this group would be relatively small, under \$10.00 per month for the average household that used gas fuel for both of these appliance categories. In addition, the degree of discretionary consumption expected in these categories is relatively small.

Finally, consumption in the unspecified category is very small and is generally associated with appliances with relatively large discretionary components. Although the saturation is, by convention, one; the expected (average) yearly household consumption in this category is extremely small. The Average Price, Marginal Price and Intra-Marginal Price are all contained in the data set. The price term specification assumes an appliance-group price response in which the within-group price response is assumed constant. Note that the price effect is applied only to the discretionary portion of the load.

## Incorporation of Socio-Economic, Lifestyle and Vintage Variables

In this section we discuss the incorporation of the socio-economic, lifestyle, and vintage variables (household characteristics) in the utility-maximization models. Household characteristics play an important role in our utility-maximization models since they may affect the tastes and budget constraints of customers. In the current discussion, our primary concerns are the household characteristics that directly affect the enjoyment or utility associated with our postulated decision variables. Table III lists such variables. Household characteristics which affect the level of utility only indirectly through their effect upon consumer options were discussed above.

Table III: Important household characteristics in the data set.

1) Number of Occupants
2) Ages of those in the home
3) The number of days occupants were away from home during the year
4) Family income
5) Age of the home
6) Work status of household members
7) House value
8) Years expected to remain in home
9) Marital status
10) Owner/renter

## Incorporating Household Characteristics in Utility Theory: A Simple Example

Consider a utility function, U, that can be used to summarize the tastes of a given household, or of the main decision maker in the household. Suppose, for simplicity that the function is log-linear and can be written:

$$U_j = a0_j + a1_j[\ln(d1)] + \dots + an_j[\ln(dn)] + e_j; \qquad (13)$$

where the j subscript for U indicates that utility has been calculated for the j'th household, $ai_j$ (i = 1,...,n) represents the i'th taste parameter for the j'th household, di (i=1,...,n) are the variables affecting the utility of the household decision maker(s), and $e_j$ is a random error term (mean zero) for the j'th household. Note that the effect of di in determining utility can vary across households. In fact, these taste parameters are probably not constant, and we may model them as functions of the characteristics of the households:

$$ai_j = fi( H_j ); \tag{14}$$

where fi is a function determining the value of $ai_j$ and $H_j$ is a vector of characteristics of household j.

In general, the parameters of the gas demand functions derived from equations like Equation (13) and a budget constraint would be related to the parameters of the original utility function. In the current setting, however, these original taste parameters were replaced by the functions used to predict them. Since the arguments of these functions are household characteristics, the household characteristics will directly affect the demand for natural gas.

## VII THE DATA SET

The variables in the customer survey data set are listed in five categories. They are: 1) service, 2) conservation, 3) family life-style, 4) appliances, 5) vintage, and 6) structural variables.

## VIII ECONOMETRIC ISSUES

The primary econometric problems adressed in the modeling effort are as follows:

1. the heteroscedasticity resulting from the overall conditional demand framework;
2. the combined heteroscedasticity and serial correlation resulting from the cross-section/time-series data analysis;
3. the simultaneity issue resulting from the use of endogenous right-side variables (price, discrete decision variables such as flow restrictor installation, etc.); and,
4. nonlinearities in the parameters in our equation specification.

## IX The Final Gas Use Equation

The final household gas use equation to be estimated is the sum of the gas end-use equations. We simplify the overall function by using notation in which the end-use equations are written as functions of the endogenous and exogenous variables. The endogenous variables are explicitly written as functions of behavioral variables such as price, income, and household characteristics. The endogenous variables are written to the left of the semicolon and the exogenous variables are written to the right of the semicolon.

In particular, we define the following notation:

$$Gi[\ e_1(H,Y,P),\ e_2(H,Y,P),\ \ldots.\ ,e_j(H,Y,P);x_1,\ x_2,\ldots,x_r\ ] \tag{15}$$

where

| | |
|---|---|
| $Gi$ | is the function describing the gas end-use consumption in end-use $i$; $i$ = sh, wh, dy, ck, ph, |
| $e_j$ (H,Y,P) | is the function describing the endogenous decision variable $e_j$ ($j$=1 to m). Although $e_j$ is explicitly dependent on the behavioral variables and implicitly dependent on engineering relationships, we list only the explicit dependencies. |
| H | is the set of household characteristics, Y is the family income, and P is the price term for this end-use, and |
| $x_k$ | is the $k^{th}$ ($k$=1 to r) exogenous explanatory variable on which Gi explicitly depends. |

## IX.1 The Final Estimating Equation

Statistical calibration of the overall model is carried out, in part, by estimating a coefficient ($a_i$) for each end-use. This coefficient relates the expected engineering usage to the actual. If the overall engineering relationships were perfectly consistent with actual consumption, the estimated value of these coefficients would be equal to positive one. Note that for some end uses, the $a_i$ would not be identifiable if there were no explicit model for the non-discretionary portion of the load. The notation of the model is consistent with that described above: the endogenous variables are written to the left of the semicolon and the exogenous variables are written to the right of the semicolon.

$$\begin{aligned}
GAS = {} & a_1 * GSH[D^*(people,ages,hday,Y,P),D_{wstrip}(ages,vintage,P,Y),\\
& \quad D_{poff}(workstat,Y,P);UA'_{shell},UA'_{infil},k_{wstrip},HEATGAIN,PILOT'_{sh}] * A_{sh}\\
& + a_2 * GWH[W^*_{wh}(people,workstat,ages,Y,P),D_{flo}(people,Y,P);\\
& \qquad UA'_{wh},\ C_{pg}\ ADW,\ k_{ADW},\ k_{flo},\ CW,\ W^*_{other},PILOT'_{wh}] * A_{wh}\\
& + a_3 * GDY[FACTOR*LOADS(people,workstat,Y,P);PILOT'_{dy}] * A_{dy}\\
& + a_4 * GCK[HRS_{ck}(ages,workstat,people,Y,P),k_{micro}(ages,workstat,people,Y,P);\\
& \qquad PCK,\ D_{micro},\ PILOT'_{ck}] * A_{ck}\\
& + a_5 * GPH[k_{cov}(people,age,hday,Y,P),D_{cov}(people,age,hday,Y,P),\\
& \qquad T_p(people,age,hday,Y,P);RCE_{ph},UACW_{ph},OTHER_{ph},PILOT'_{ph}] * A_{ph}\\
& + a_6 * GMISC\ [people,\ age,\ hday,\ Y,P]\ + U_{GAS};
\end{aligned} \tag{16}$$

where

$U_{GAS}$ is a disturbance term,

$a_i$ is the estimated adjustment coefficient on appliance i (i = space heater, water heater, clothes dryer, cooking appliances, pool heater, unspecified), and

$A_i$ = 1 if appliance i is present, 0 otherwise (i = space heater, water heater, clothes dryer, cooking appliances, pool heater, unspecified).

The endogenous decision variable functions in equation (16) are:

Previously defined: $D_{wstrip}$, $D_{poff}$, $D^*$, $D_{flo}$, $FACTOR*LOAD$, $T_p$, $D_{cov}$
Previously undefined:

$W^*_{wh}$ = $(W^*_{dish}, W^*_{cloth}, W^*_{bath}, W^*_{shower})$

$k_{micro}$ = $(k_{micro,top}, k_{micro,oven})$

$HRS_{ck}$ = $(HRS_{top}, HRS_{oven})$,

$k_{cov}$ is the function describing the proportionate savings in radiation and convection and evaporation due to a pool cover, and

The previously undefined exogenous variables in Equation (16) are:

people is the number of people in the home,

ages is the average age of the household members,

workstat is the work status of the household members,

hday is the number of people home during the day,

$k_{ADW}$ is the proportionate increase in hot water usage due to the presence of an automatic dishwasher,

$k_{flo}$ is the proportionate savings due to the shower flow restrictor,

$W^*_{other}$ is the number of degree-gallons of hot water used for other hot water applications,

$PILOT'_{dy}$ is the pilot light load of the dryer,

PCK = (PRT,POV),

$D_{micro}$ is a binary variable representing the presence of a microwave oven,

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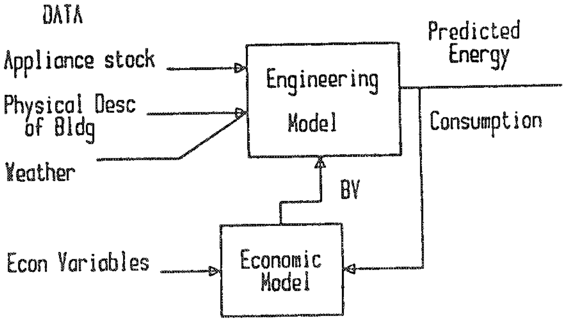

Figure 1: The integrated Engineering and economic model.

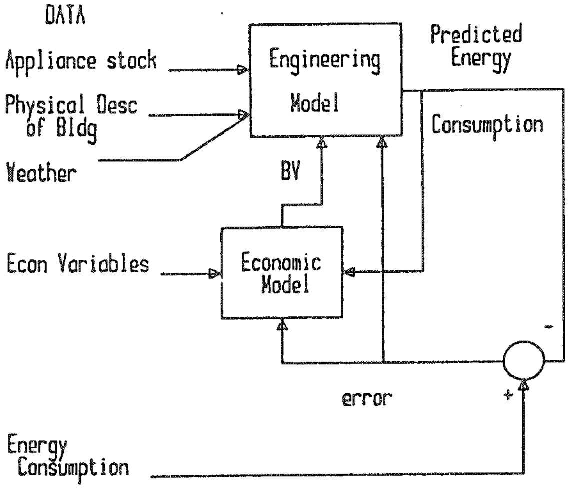

Figure 2: Calibration of the integrated model.