Using conditional demand analysis to estimate residential energy use and energy savings

K. H. Tiedemann
BC Hydro
Canada
ken.tiedemann@bchydro.com

Keywords
end-use consumption, energy efficiency, residential dwellings, conditional demand analysis, regression analysis.

Abstract
Utilities require detailed end-use energy consumption for power system planning, load forecasting, marketing and demand side management. End-use consumption refers to the consumption of space heating, space cooling, water heating, lighting and other specific uses as opposed to total consumption. This report presents the methodology and results of a residential end-use study for British Columbia, Canada. The study used Conditional Demand Analysis (CDA) to estimate Unit Energy Consumption (UEC) values for several residential end-uses and for several energy conservation measures. Conditional demand analysis is a multivariate regression technique which combines utility billing data with weather information and customer survey data to produce robust end-use energy consumption estimates.

Introduction
End-use energy consumption information is becoming increasingly important for power system planning, load forecasting, marketing and demand side management. A key tool for estimating end-use energy consumption is conditional demand analysis, which uses energy billing data combined with weather data and customer survey data in a multivariate regression framework. The basic idea underlying the conditional demand analysis is that the total load can be disaggregated into the component or end-use loads. These in turn can be modeled using thermodynamic principles as appropriate. The conditional demand analysis framework has several advantages over its main rival of end-use metering. First, surveying customers is inexpensive compared to end-use metering, so that robust estimates can be produced at relatively low cost through conditional demand analysis. Second, the number of sites included in metering projects is often quite small, so that the metered estimates may have large standard errors compared to CDA estimates. Third, the conditional demand approach can be used to estimate end-use loads in residential dwellings or dwelling classes not included in the modelling, if appropriate survey-based information is available. A number of previous studies have used conditional demand analysis to estimate residential end-use consumption. These studies include Lawrence and Parti (1984), Parti and Parti (1989), Sebold and Paris (1987), and Tiedemann (1997a, 1997b). The present study extends the commonly applied conditional demand analysis framework in order to produce both end-use consumption and end-use savings estimates.

Method
This study applies the conditional demand model. The basic idea of the conditional demand model is that total household consumption is the sum of consumption of various end-uses plus an error term or residual. Appliance saturations are modeled by an indicator variable to indicate the presence or absence of an end-use in a particular household or by a count variable to indicate the number of units present. The estimated regression coefficient is the unit energy coefficient or UEC. The UECs are modeled as functions of appropriate exogenous variables. The detailed model uses a combined behavioral-thermodynamic approach. In other words, basic thermodynamic relationships

Table 1. Regression results

Component	Coefficient	Standard error	P-value
HDD*Area*MainElecspaceheat	0.047	0.002	0.00
HDD*Area*Duplex*MainElecspaceheat	-0.015	0.002	0.00
HDD*Area*Apartment*MainElecspaceheat	-0.046	0.003	0.00
HDD*Area*Mobilehome*MainElecspaceheat	0.059	0.004	0.00
HDD*Area*Highinsulation*MainElecspaceheat	-0.013	0.001	0.00
HDD*Area*Effwindows*MainElecspaceheat	-0.0040	0.002	0.01
HDD*Area*Income*MainElecspaceheat	0.00000023	0.000	0.00
Area*Winter*Mainelecspaceheat	6.48	0.586	0.00
HDD*Area*Nonelecsecspaceheat*MainElecspaceheat	-0.0019	0.001	0.14
HDD*Area*Secondaryelecspaceheat	0.017	0.001	0.00
HDD*Area*Duplex*Nonelecsecspaceheat	-0.013	0.003	0.00
HDD*Area*Apartment*Nonelecsecspaceheat	0.056	0.008	0.00
HDD*Area*Mobilehome*Nonelecsecspaceheat	-0.00083	0.003	0.79
CDD*Area*Central space cooling	0.059	0.011	0.00
CDD*Area*Room or portable space cooling	0.066	0.012	0.00
HDD*Elecwaterheat	0.153	0.077	0.05
HDD*log(NoPeop+1)*Elecwaterheat	0.934	0.186	0.00
HDD*log(NoPeop+1)*High insulation*Elecwaterheat	0.464	0.129	0.00
HDD*Dishwasher loads per week*Elecwaterheat	0.091	0.008	0.00
HDD*Clotheswasher loads per week*Elecwaterheat	0.017	0.007	0.02
HDD*No lowflow showerheads*Elecwaterheat	-0.083	0.040	0.04
HDD*No instant hotwater taps*Elecwaterheat	0.366	0.056	0.00
HDD*No waterheaterblankets*Elecwaterheat	-0.195	0.051	0.00
No refrigerators and freezers	92.7	5.21	0.00
No electric ranges and cooktops ando vens	60.1	8.69	0.00
No dishwashers	3.20	10.6	0.76
No clothes washers and dryers	54.0	7.88	0.00
No incandescent lamps	3.35	0.302	0.00
No fluorescent lamps	5.72	0.904	0.00
No compact fluorescent lamps	-3.88	0.904	0.00
No halogen lamps	14.2	0.908	0.00
No other lamps	-0.053	0.582	0.90
No televisions	73.2	4.57	0.00
No personal computers	54.7	6.08	0.00
Pool	326.0	28.0	0.00
Indoor hot tub	136.4	16.6	0.00
Outdoor hot tub	362.1	17.0	0.00
R-squared	0.83		
F-statistic	2367		

Note. HDD is number of heating degree-days; CDD is number of cooling degree-days; no is number; log is logarithm; elec is electric; nonelec is non-electric; unless otherwise indicated the variable is an indicator variable.

are exploited to define equations reflecting energy consumption for major end-uses, and these are modified by behavioral characteristics such as the manner and frequency with which an end-use is employed.

The dependent variable in the model is daily energy consumption per household in a given month, which is obtained from customer billing data by dividing total consumption by the number of days in the billing cycle. Using customers' actual consumption by month allows consumption to be modeled as a function of weather in that month, including the impact of heating degree-days (HDD) on main space heating and supplementary space heating load and the impact of cooling degree-days (CDD) on central air conditioning and portable/room air conditioning loads.

This study is based on a survey of residential customers in BC Hydro's service territory who participated in the 2004 Residential End-Use Survey. For this study, surveys were mailed to 3,639 residential customers in November 2004. This survey covering all major end uses, housing characteristics and demographics, as well as attitudes towards energy use. The total number of surveys returned was 928, with unusable ID numbers and missing billing data reducing the usable sample to 791 surveys. Survey information was merged with energy consumption information for the period January 2004 through December 2005 and with weather data from a weather station closest to their dwelling.

The condition demand model was estimated using ordinary least squares to increase comparability with previous studies. The regression results are summarized in Table 1, which shows the value of each regression coefficient, the standard error and the associated probability that the coefficient is different from zero. The overall regression performed well with an adjusted R-squared value of 0.83. All coefficients had the expected signs, and 34 of 37 coefficients were significant at the 5 % level or better.

End-use energy consumption

The regression coefficients were used to calculate unit energy consumption values for major residential end-uses. This involved the following steps:

1. calculate the UEC for each household possessing that end-use for each month by substituting household values and normal heating degree-days and cooling degree-days into the end-use equations;
2. calculate weighted average UECs across all households possessing that-use for each month; and
3. calculate the aggregate results across months.

Table 2. Saturation rates, unit energy consumption and end-use intensity

	Saturation (number per household)	Unit energy consumption (kWh peryear)	End-use intensity (kWh per year)
Primary electric space heating	0.28	5,037	1,410
Secondary electric space heating	0.29	2,310	670
Central air conditioning	0.07	346	24
Room or portable air conditioning	0.14	207	29
Electric water heater	0.42	3,186	1,338
Refrigerator and freezer	2.11	1,112	2,346
Electric range, cook top and oven	1.07	721	771
Dishwasher	0.77	38	29
Clothes washer and clothes dryer	1.80	648	1,166
Lighting	1.00	1,937	1,937
Television	1.93	878	1,695
Personal computer	1.11	656	728
Swimming pool	0.05	3,912	1,956
Hot tub	0.17	2,618	445
Total consumption			12,744

Table 3. Saturation rates, unit energy savings and end-use savings

	Saturation (number per household)	Unit energy savings (kWh peryear)	End-use savings (kWh per year)
High insulation levels/insulated doors	0.26	1,649	429
Energy efficient windows	0.12	618	74
Low flow shower heads	0.40	256	102
Only full laundry loads	0.90	162	146
Water heater blanket	0.14	616	86
Compact fluorescent lamps	3.9	47	183
Total savings			1,020

Table 2 provides the saturation rates, unit energy consumption and end-use intensities, as well as total end-use intensity per household. The saturation rate is the average number of that end-use per household. The end-use intensities are the product of saturation rates multiplied by unit energy consumption. In other words, the unit energy consumption is average electricity consumed by that end-use if it is present, while the end-use intensity is the average consumption of that end-use across all households. The largest UECs include primary electric space heating (5,037 kWh per year), secondary electric space heating (2,310 kWh per year), electric water heater (3,186 kWh per year), lighting (1,937 kWh per year), swimming pool (3,912 kWh per year) and hot tub (2,612 kWh per year).

End-use energy savings

The regression coefficients were also used to calculate unit energy savings values for major residential energy conservation measures. This involved the following steps:

1. calculate the unit energy savings for each household possessing that measure for each month by substituting household values and normal heating degree-days and cooling degree-days into the end-use equations;
2. calculate weighted average unit energy savings across all households possessing that measure for each month; and
3. calculate the aggregate results across months.

Table 3 provides the saturation rates, unit energy savings and end-use savings, as well as end-use savings per household. The saturation rate is the average number of that measure per household. The end-use savings are the product of saturation rates multiplied by unit energy savings. In other words, the unit energy savings is average electricity saved by that measure if it is present, while the end-use savings is the average savings of that measure across all households. The largest unit energy savings include high insulation levels/insulated doors (1,649 kWh per year), energy efficient windows (618 kWh per year), low flow shower heads (256 kWh per year), and water heater blankets (616 kWh per year).

Monthly end-use and energy savings estimates and load factor

A particularly useful feature of the conditional demand model is that it allows for the calculation of monthly end-use consumption and monthly savings estimates. This is useful in understanding the determinants of monthly loads for utilities, such as BC Hydro, where daily consumption varies substantially over the course of the year. Table 4 provides information on the monthly end-use intensity for five major weather related loads: primary electric space heating, secondary space heating, central air conditioning, room or portable air conditioning and water heating. It is worth noting that BC Hydro's system peak typically occurs on a cold winter day in November, December, January or February. Primary electric space heating and electric water heating are the main residential (and overall) drivers of this peak as shown in the table. There is also a secondary summer peak that typically occurs in June, July or August. Central

Table 4. Monthly end-use intensity (kWh per month)

	Primary electric space heating	Secondary electric space heating	Central air conditioner	Room or portable air conditioner	Water heating
January	897	357	0	0	486
February	807	305	0	0	415
March	528	285	0	0	391
April	385	204	0	0	283
May	257	133	4	2	188
June	121	61	36	23	88
July	50	24	162	95	37
August	53	24	34	80	40
September	152	79	10	7	114
October	372	200	0	0	275
November	518	282	0	0	385
December	898	356	0	0	484
Total	5,037	2,310	346	207	3,186

Table 5. Approximate load factors for weather related end-uses (percent)

End-use	Primary electric space heating	Secondary electric space heating	Central air conditioner	Room or portable air conditioner	Water heating
	46.8	53.9	17.8	18.2	54.6

Table 6. Monthly end-use savings (kWh per month)

	High insulation levels/insulated doors	Energy efficient windows	Low flow shower heads	Water heater blankets
January	250	96	39	95
February	215	81	33	81
March	203	75	32	75
April	147	53	23	54
Amy	98	35	15	36
June	46	16	7	17
July	19	7	3	7
August	21	8	3	8
September	59	22	9	22
October	143	54	22	53
November	199	75	31	75
December	250	95	39	94
Total	1,649	618	256	616

air conditioning and room or portable air conditioning are main residential drivers of this secondary peak.

For each end-use, an approximate load factor can be estimated by dividing average monthly consumption by peak consumption. This approximation does not take into consideration variation in the load over the course of a day, but still provides insight into what is driving the peak load. For winter peaking end-uses this provides an estimate of the impact of the end-use on winter system coincident peak, while for summer peaking uses this provides an estimate of the impact on summer peak. As might be expected water heating is the flattest of the five loads examined here, while central air conditioning and room or portable air conditioning are the peakiest loads.

Table 6 provides information on the monthly end-use savings for four major weather related energy conservation measures: high insulation levels/insulated doors, energy efficient windows, low flow shower heads and water heater blankets. All four measures have the biggest impacts on the system winter peak, with high insulation levels/insulated doors having the biggest energy savings, followed by energy efficient windows, water heater blankets and low flow shower heads.

Finally for each energy conservation measure, an approximate load factor can be estimated by dividing average monthly consumption by peak consumption. Again, this approximation does not take into consideration variation in the load over the course of a day, but still provides insight into what is driving the peak load.The approximate load factor for each measure is around 55 % and these are, of course, all system peak coincident numbers.

Table 7. Approximate load factor (percent)

Measure	High insulation levels/insulated doors	Energy efficient windows	Low flow shower heads	Water heater blankets
	55.0	53.6	54.7	54.0

Conclusions

Utilities require detailed end-use energy consumption for power system planning, load forecasting, marketing and demand side management. End-use consumption refers to the consumption of space heating, space cooling, water heating, lighting and other specific uses as opposed to total consumption. This report presents the methodology and results of a residential end-use study for British Columbia, which uses Conditional Demand Analysis (CDA) to estimate unit energy consumption (UEC) values for several residential end-uses and for several energy conservation measures. CDA is a multivariate regression technique which combines utility billing data with weather information and customer survey data.

The study produced unit energy consumption estimates for 14 end-uses and four energy conservation measures based on a sample of 791 residential customers. The results were weighted to the population of B.C. Hydro customers. As expected, the largest end-uses are primary electric space heating at 5,037 kWh per year and electric water heating at 3,186 kWh per year. Other major end-uses are secondary electric space heating (2,310 kWh per year), lighting (1,937 kWh per year), refrigerator and freezer (1,112 kWh per year), television (878 kWh per year) and electric range, cook top and oven (721 kWh per year). Major conservation measures included insulation and draft proofing (1,649 kWh per year), energy efficient windows (618 kWh per year), low flow shower heads (256 kWh per year) and water heater blankets (616 kWh per year).

The conditional demand model also produces information on monthly end-use consumption and load factors. BC Hydro's system peak typically occurs on a cold winter day in November, December, January or February. Primary electric space heating and electric water heating are the main residential (and overall) drivers of this peak as shown in the table. There is also a secondary summer peak that typically occurs in June, July or August. Central air conditioning and room or portable air conditioning are main residential drivers of this secondary peak. An approximate load factor can be estimated by dividing average monthly consumption by peak consumption. This approximation does not take into consideration variation in the load over the course of a day, but still provides insight into what is driving the peak load. For the five loads examined, water heating is the flattest of the five loads examined here, while central air conditioning and room or portable air conditioning are the peakiest loads.

References

Lawrence, D. and M. Parti, 1984, Survey of conditional energy demand models for estimating residential unit energy consumption coefficients, EPRI Report No. EA-3410.

Parti, C. and M. Parti, 1989, The total and appliance-specific demand for electricity in the household sector. Bell Journal of Economics, Vol.11, Spring 1989, pp. 309-324.

Sebold, F. and K. Paris, 1989, Residential end-use energy consumption: a survey of estimates, EPRI Report No. CU-6487.

Tiedemann, K., 1997a, Estimating residential end-use energy consumption, Proceedings of the Eleventh Annual Symposium on Geographical Information Systems, pp. 616-618.

Tiedemann, K. 1997b, Statistical modeling of end-use energy consumption using a residential panel, Proceeding of the 5th International Conference on Probability Methods Applied to Power Systems, pp. 398-342.

BC Hydro, 2004, 2004 Residential end-use survey.

Acknowledgment

I would like to thank Joe Kelly for his assistance with the modelling for this study.