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Use of Wood for Space Heating: Analysis of Hood River Conservation Project Submetered Homes

Bruce Tonn
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EXECUTIVE SUMMARY

This report analyzes wood use in the 100 homes that had wood channel submeters installed as part of the Hood River Conservation Project (HRCP). It complements previous work by Tonn and White (1986) on wood use for residential space heating in the Pacific Northwest and current research by other analysts on other aspects of HRCP. Specifically, this report develops wooduser profiles, and assesses the magnitude of electricity displaced by wood, patterns of wood and electricity use, and determinants of wood use.

Five types of data were used in this analysis. The most important data are the 15-minute pulse, submeter readings taken on four channels. The channels are kWh for electric space heating, kWh for total electric use, kWh for wood use/water heating (100 households for the former, 220 households for the latter), and Fahrenheit degrees (^{o}F) for indoor temperature. The kWh for wood heat were derived from radiometer data that measured heat output from wood burning equipment. In addition to these data, demographic data are available from the 1983 Pacific Northwest Residential Energy Survey (PNWRES), a special Wood Heating Survey, and Project related data sets. Four years of electricity billing histories were also utilized. As a collection, the data resources are unique and extremely rich.

Numerous interesting findings resulted from each area of analysis. With respect to wooduser profiles in the Pacific Northwest, it was found that:

- woodusers have larger homes;
- woodusers have larger families;
- woodusers have older homes;
- heavy woodusers have higher incomes than other woodusers;
- households use wood for strictly economic reasons; and
- woodusers mostly consume low quality wood but use high quality wood as secondary sources.

An analysis of electricity displacement by wood use found that:

- wood-using homes produce from 1.7 (1985/86) to 4.5 (1984/85) times more energy for space heating by wood than by electricity;
- the total space heating energy requirements are nearly 20% larger for woodusers than for nonwooduser households;
- woodusers saved over 53% more total space heating energy than nonwoodusing households;

- investments in energy conservation measures made in heavy wood-using households were most efficient for saving energy; and

- investments in energy conservation measures made in nonwoodusing households were most efficient for saving electricity.

With respect to patterns of wood/electricity use, it was found that:

- several major patterns appeared both before and after houses received weatherization, and generally constitute patterns of high wood/low electricity use, high electricity/low wood use, and low wood/low electricity use patterns;

- the patterns do not correlate well with specific days of the week;

- the patterns correlate strongly with variations in outdoor temperature--low wood/low electricity use patterns are most used in mild temperatures, whereas a variety of patterns are used in very cold conditions;

- households do not change patterns often; and

- high electricity patterns are associated with households that have higher incomes and smaller families whereas high wood use patterns are associated with households that have larger, less energy efficient homes.

The econometric results are derived from a three stage least squares lagged dependent variable, simultaneous equation system model. The model was estimated using household survey, HRCP, and submetered data. Among many interesting insights from this analysis were:

- there is little interdependence among wood use, electricity use, and indoor temperature;

- household decisions concerning electricity use for space heating appear to precede wood use and indoor temperature decisions;

- previous-year wood and electricity use variables are all highly significant, indicating that the proportions of electricity and wood use due to retrofit changed only marginally;

- houses with central heating use more electricity than noncentrally heated houses;

- houses receiving more conservation measures use less electricity than those receiving only minimal measures;

- households with toddlers use less wood and favor electricity use; and

- households that have favorable attitudes toward conservation have lower indoor temperature preferences.

The results presented in this report should contribute to the many policy analyses regarding residential electricity demand and supply, for three main reasons. First, wood displaces a great deal of electricity in woodusing households. Utilities desiring to increase electricity demand could market woodusing households, which tend to have the characteristics mentioned above. Second, the econometric model indicates that electricity use decisions appear to precede wood use decisions. This suggests that changes in electricity prices could have a volatile affect on electricity demand and then on wood use, since wood is a flexible space heating substitute. Third, weatherizing both nonwoodusing and woodusing homes provides Bonneville benefits by reducing the magnitude of potential savings in residential electricity demand.

Several problems limited this research; their solutions provide directions for future work. First, all households with submetering should have been asked to complete the Wood Heating Survey and all nonwoodusers should have been instructed to complete the attitude questions pertaining to wood use. Second, better price data with respect to both wood (e.g., through surveying local venders) and electricity could have enabled rigorous price elasticity analyses. Third, more time series data on changes in household demographics could have contributed to a better understanding of changes in energy consumption.

Additional comments pertain to suggestions for more complex econometric analysis of existing data. Specifically, new econometric tests for simultaneity between wood use and electricity use could be applied to the data. Lastly, Bonneville might consider applying artificial intelligence techniques in the area of machine learning to develop models of how individual households alter wood and electricity use given outdoor temperatures, day of the week, and other variables that have been shown here to be relevant.

ABSTRACT

This report analyzes wood use in the 100 homes that had wood channel submeters installed as part of the Hood River Conservation project. In addition to wood heat output data, data were also available on electricity use, house characteristics, household demographics, and weatherization measures installed. The data indicate that in wood using homes, space heat produced by wood burning is approximately twice as much as provided by electricity. Woodusers tend to have larger homes and families and use wood for strictly economic reasons. Patterns of wood and electricity use for space heating do not vary much by day of week but are strongly correlated with outdoor temperatures. The large residential demand for wood may present difficult power planning problems for the Bonneville Power Administration if households suddenly switch back to electricity. However, conservation programs provide Bonneville benefits by dampening the magnitude of any potential swings.

INTRODUCTION

The Hood River Conservation Project (HRCP) was a major residential retrofit demonstration project, operated by Pacific Power & Light Company (PP&L) and funded by the Bonneville Power Administration. The project sought to install as many cost-effective retrofit measures in as many electrically-heated homes as possible in the community of Hood River, Oregon. Energy audits were conducted and retrofit measures were installed by HRCP between fall 1983 and the end of 1985. Data collection and analysis began in spring 1984 and may continue through 1988.

The $20 million project involved higher levels of conventional retrofit measures than generally offered in weatherization programs in the Pacific Northwest [e.g., R-49 ceiling insulation rather than the R-38 generally recommended in the Bonneville Residential Weatherization Program (RWP)]. Bonneville paid for installation of these measures up to a cost-effectiveness limit ($1.15/first-year estimated kWh savings) that is almost four times the limit in the Bonneville Residential Weatherization program. Thus, HRCP offers the chance to examine levels of retrofit installation and subsequent energy savings when cost to the household and prior retrofit activities are largely removed as barriers.

The town and county of Hood River (plus the town of Mosier in Wasco County) were selected as locations for this experiment because the area is geographically delimited: it includes a diversified economy, population, and housing stock; the area is served by both public and private utilities (Hood River Electric Cooperative (HREC) and PP&L); and it encompasses climate zones representative of the Pacific Northwest. Hood River County has a population of about 15,000. Roughly two-thirds of the 6,200 residences are served by PP&L and the remainder by HREC.

Hood River lies along the northern edge of Oregon by the Columbia River, 60 miles east of Portland.

The contract between Bonneville and PP&L to initiate this project was signed in May 1983, after more than a year of planning. Energy audits were first offered in fall 1983 and installation of retrofit measures began in early 1984. Roughly 15% of the retrofit installations were completed in 1984, with the remainder done in 1985. All Hood River households were eligible for a free home energy audit. However, the project paid for installation of retrofit measures only in homes with permanently installed (before March 1983) electric space heating equipment. Of the roughly 3,500 eligible households, 2,988 (85%) received one or more HRCP-financed major retrofit measures. An additional 201 homes (6%) received an energy audit only.

This report has several purposes. Foremost, it extends research performed by Oak Ridge National Laboratory (ORNL) for the Bonneville Power Administration into the use of wood for residential space heating by households in the U.S. Pacific Northwest. An earlier report by Tonn and White (1986) utilized the 1979 Pacific Northwest Residential Energy Survey (PNWRES), histories of electricity bills, and survey data collected as part of ORNL evaluations of Bonneville residential conservation programs to track trends in residential wood use. The discussion herein focuses on wood use by the 320 homes monitored* as part of the Hood River Conservation Project in relation to wood use, indoor temperatures, electricity use for space heating, water heating, and all end uses in total. One hundred homes received wood use submeters and 220

*Throughout this report, "monitor" and "submeter" are used interchangeably.

received water heater submeters in place of wood use submeters. Most of the analyses reported below focus on the sample of wood monitored households, although the water-heating monitored households are included in numerous analyses.

The submetered data, in conjunction with electricity billing histories, audit recommendations, energy conservation measure installations, specially collected weather data, and comprehensive household surveys, represent a unique resource for the study of residential energy conservation. As such, this report serves as a companion to numerous other HRCP studies. Hirst (1987) summarizes the entire Hood River Study; Hirst, Goeltz, and Trumble (1987) document energy savings due to HRCP; Dinan (1987) analyzes changes in indoor temperature preferences related to HRCP; Stovall (1987) examines load shifting; and Brown, White, Purucker, and Hirst (1987) assess electricity savings associated with water heating. This report contributes to these other efforts by providing a rigorous analysis of wood use in the monitored homes.

Section 1 discusses the data sets used in the various analyses. The submetered data set for the 320 homes, collected from mid-1984 to mid-1986, consists of fifteen-minute pulses of electricity kWh for space heating, total electricity kWh, kWh equivalent from wood burning (100 homes), electric kWh for water heating (220 homes), and indoor temperature (^{o}F). For each home, data are also available describing results of each house's energy audit, and costs and predicted savings of installed energy conservation measures. In 1984, each of the 320 households completed the 1983 PNWRES survey, which inquires about past energy conservation behavior, attitudes, demographic characteristics, and house characteristics. In 1986, a subset of the 320 homes completed the Wood

Heating Survey, which inquires about wood use levels, attitudes toward wood use, and intentions pertaining to future wood use.

Section 2 presents summary statistics designed to create images of woodusers. Profiles are developed using demographic characteristics, reported levels of wood use, attitudes toward wood use, and types of wood burned. The following section addresses electricity consumption for space heating displaced by wood use. Billing histories and sub-metered data both indicate that in the 100-home sample, wood represents over 50% of total space heat energy. Analytical assessments are performed to explore the cost effectiveness of installing retrofit measures in homes that use wood.

The fourth section probes wood use patterns. The fifteen-minute data offer an excellent opportunity to visually analyze wood and electricity use during representative days. Cluster analyses were performed to find typical daily wood and electricity use patterns, both pre- and postretrofit. Additional cluster analyses were performed to explore whether households utilize different sets of these patterns.

Section 5 revolves around the development of a complex econometric model designed to explore the determinants of wood use. The model incorporates four dependent variables: wood use, electricity use for space heating, electricity use for other end uses, and indoor temperature. Lagged dependent variables were included and the model was estimated using Three Stages Least Squares (3SLS). A primary goal was to utilize the opportunity to study wood use as part of the entire household energy use environment, and to explore whether wood use decisions precede or follow other energy use decisions. The last question is important to Bonneville, for if wood use decisions precede electricity use decisions, then factors that change about wood would drive changes in electricity demand more than changes in factors about electricity. If electricity decisions precede wood decisions and if electricity factors change radically, then Bonneville may need to plan for potentially large swings in electricity demand. Use of the submetered data to compose the dependent variables makes this modeling effort unique.

The main body of the report concludes with a summary of findings and recommendations for future work. The recommendations focus on data that could have significantly contributed to this study had they been available. Two appendices follow the main body of the report. Appendix A contains a discussion on the quality of the data that were used. Much attention focuses on explaining how the submetered data were collected. In addition, potential survey data inconsistencies are reviewed. Appendix B presents a rough analysis of the magnitude of virtual conservation installed in the 100 wood-monitored homes, how conservation narrows the possible swing in electricity demand by these homes, and what might happen if households switch energy use patterns.

1. DATA USED IN THE REPORT

At least one social scientist has referred to the Hood River Conservation Project as "an evaluator's dream." No less than ten data sources were tapped for developing the database to evaluate HRCP (Hirst and Goeltz, 1986). The objective of this study--analysis of wood use for space heating in the submetered homes--means that only a part of the wealth of data will be used. The data sources are described first; sample sizes are discussed in the second half of this section.

1.1 DATA SOURCES

Figure 1.1 shows the types and collection dates for the five data sets that are used in this report. Monthly electric utility bills were collected for HRCP program participants and nonparticipants for the

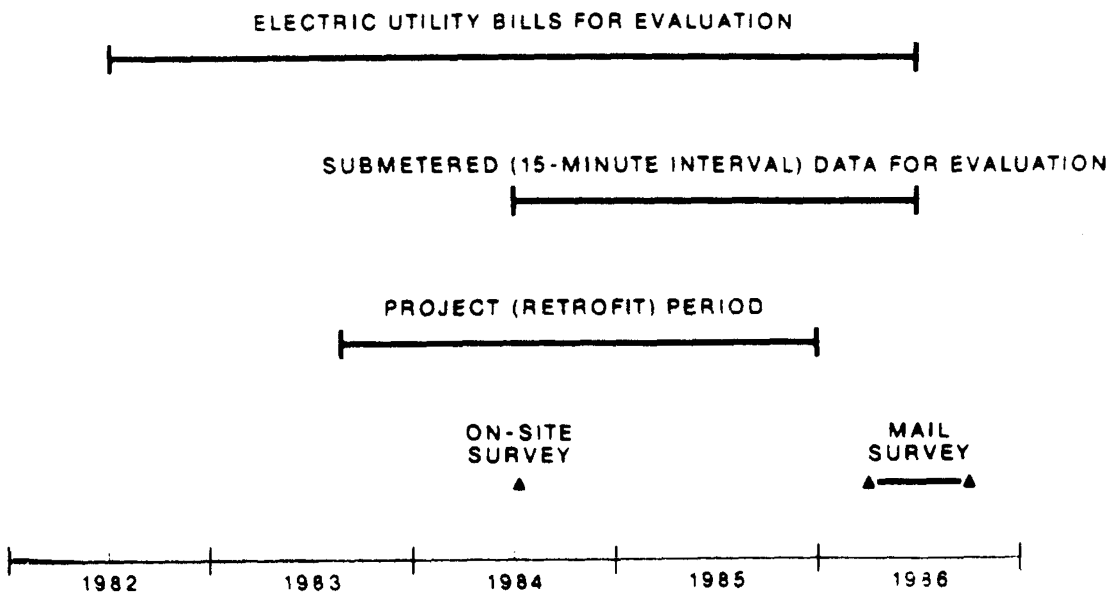

Figure 1.1 Time line of data collection and HRCP program activities related to this study.

period July 1982 through June 1986. These bills were supplied by PP&L and the Hood River Electric Co-op, two electric utilities serving the Hood River community.

Approximately ten percent of the 3,249 project participants (320 households) were selected for monitoring of end use loads. The actual houses selected for monitoring were identified from a total list of Hood River customers for each utility. The PP&L list was randomized using a SAS procedure. Sampling from the Co-op list was accomplished by systematic random sampling using the Co-op billing books. Each customer was called by telephone until 10 percent, or 320 households, had agreed to have their homes submetered. A similar process was used in the identification of households that use wood for space heating. Wood space heating submeters were eventually placed in 100 of the 320 submetered homes. Submetered data were collected at 15-minute intervals for each of three end uses--total electricity consumption (kWh), electric space heating (kWh), and wood heat output (kWh) or electric water heating (kWh)--and for indoor temperature.

The collection of the wood heat data required careful attention to instrumentation and data validity. Wood heat output is directly measured by one radiometer placed in a strategic location near the wood burning equipment. Typically, the radiometers were placed and aimed at the left rear of the stove. Laboratory experiments performed by Modera, Wagner, and Shelton (1984), analysis of secondary data sources by Modera (1986), and extensive examination of each stove site were used to assure closely correlated radiometer readings with actual stove heat output. Straightforward calculations were used to convert radiometer data recorded in volts to kWh units needed to facilitate comparison of wood heat output and electricity consumption. Details concerning the wood heat data collection process are found in Appendix A.

Each HRCP participant received an energy audit. Independent contractors applied Bonneville's Standard Heat Loss Methodology (SHLM) to estimate heat loss and potential savings for each of the eligible conservation measures (Table 1.1). All households selected for submetering were retrofit during the summer of 1985, thereby providing HRCP evaluators with one year of preretrofit submetered data (July 1984 through June 1985) and one year of postretrofit submetered data (July 1985 through June 1986).* During the audit, additional information was collected on the household's demographic characteristics and reasons for participation. The home's structural characteristics and sources of information about HRCP were also obtained. An inspection was conducted after retrofit work was completed. Information was collected about the measures installed and about questions not answered during the original audit. The period from original audit to retrofit is referred to as the "project (retrofit) period" in Fig. 1.1.

In addition to electric utility bills, submetered (15-minute interval) data, and data from the project (retrofit) period, two surveys were administered to households with the submetered energy channels. During the late spring and early summer of 1984, the 1983 Pacific

*Most audits of the submetered homes were conducted late in 1983. The scheduling of retrofit work for 1985 applied only to the submetered homes; for the other households, program managers desired to begin retrofit work within 30 days of the original audit. Other analyses of HRCP might select July 1982 through June 1983 as the preretrofit year in view of the long audit and retrofit period. We caution users of this and other HRCP evaluations to be aware of this and other differences resulting from audit and retrofit dates, the sample of participants under study, and the objective of the evaluation.

Table 1.1 Measures eligible for retrofit under the Hood River Conservation Project

1. Ceiling insulation: R-49
2. Floor insulation: R-38
3. Wall insulation: R-11 to R-9
4. Duct insulation: R-11, R-30, as applicable
5. Storm window: triple glazing
6. Sliding glass door: double glazing
7. Window/door caulking: where applicable
8. Window/door weatherstripping: where applicable
9. Clock thermostat: where applicable
10. Heat exchanger: as required
11. Water heater wrap: R-11
12. Water pipe wrap: R-3
13. Low-flow showerhead installation: as required
14. Outlet gasket installation: where applicable
15. Heat pump conversion of existing furnace system: in special circumstances

Northwest Residential Energy Survey (PNWRES) was administered on-site to 314 of the 320 submetered homes. More than 300 questions were asked regarding demographic and household characteristics, structure characteristics, energy conservation attitudes and behaviors, and conservation activities since 1980. Questions on primary and secondary space heating fuel use provide one basis for the identification of woodusers and heavy woodusers among all of the submetered households.

A specially designed Wood Heating Survey was administered to a random sample of HRCP participants in 1986.* Although only 200 mail surveys are available for this study for those households with both a 1984

*The 1986 survey was administered during two separate periods of 1986. A low response in the spring (barely 50%) encouraged project managers to readminister a refined survey instrument in the fall. To ensure representativeness of the survey, eight random samples of HRCP participants were generated. The random sample that maximized overlap with the spring respondents was selected. The survey was then administered to the part of the sample that had not responded to the initial 1986 survey. As a consequence of this approach, the overall response rate was elevated to 82%.

and a 1986 survey, the two surveys complement one another. The 1986 survey asked for more than 120 pieces of information regarding current demographic characteristics, wood use behavior, and expected future wood use. These data are used in the wooduser profiles and electricity displacement analyses found in Sections 2 and 3, respectively.

1.2 SAMPLE SIZES

Table 1.2 represents the various sample sizes and their data sources used in this analysis. Households were removed from the database when either all submetered data for the given end use (wood or

Table 1.2 Sample sizes for the wood heating analysis[a]

Data sources[b]	All submetered Homes	Channel	
		Wood Heating	Water Heating
Total	320	100	220
After cuts 1 and 2[c]	304	92	212
Billing histories	304	92	212
Submetered data	304	92	212
Audits	304	92	212
1984 Survey	298	91	207
In residence since 7/82	246	76	170
1986 Survey	200	55	145
In residence since 7/82	163	46	117

[a]Data analysis frequently depends on information derived from the intersection of data sources. As a result, sample sizes (N) appearing in illustrations and in text might differ slightly from the sample sizes presented here. Generally, however, if the 1984 survey or the 1986 survey is available, then so are the billing history and submetered data.

[b]Each row in this table represents the number of households that had complete data for that row and all the rows above it. For example, the audits row indicates that 304 homes have complete audit data as well as complete billing history and submetered data.

[c]Houses cut in Step 1 did not have satisfactory submetered data and those cut in Step 2 had shared a utility electricity meter with other housing units.

water heating channel) were missing for one or both years or the household's regular electric bills were maintained as part of a multi-metered account.

Throughout this report, the data sources are referred to as follows: the 1984 survey is also called the PNWRES Survey; the 1986 survey is also the Wood Heating Survey; audits are both "project (retrofit) period" data, and project data; NAC, an abbreviation for normalized annual consumption, is another term for the billing histories; and the submetered data at 15-minute intervals or other temporal summaries will be referred to as either monitored data or end use load data.

2. WOODUSER PROFILES

This section presents descriptive statistics useful in creating images of woodusers. "Wooduser" is defined as a household that self-reported wood as a primary or supplemental space heating fuel or that burned some amount of wood, measured in cords, during the 1983/84 heating season.*

As with any complex picture, one's appreciation of a wooduser profile depends upon what aspect of the picture one focuses on. To provide a richer understanding, four different views are analyzed. The first is demographic; what standard demographic variables set woodusers apart from nonwoodusers? The second explores trends in cords consumed by woodusers and also probes the reliability of household reports on cords consumed. Summaries of attitudes about wood use represent the third view and descriptions of the kind of wood being burned represent the fourth.

2.1 WOODUSER DEMOGRAPHICS

In a previous study, Tonn and White (1986) found that woodusers in the Pacific Northwest tend to have larger families, larger homes, older homes, and newer primary space-heating equipment, and to live in rural areas. Woodusers among the 320 monitored households, including the 100 households with wood-heat channels, have similar characteristics (Table 2.1). For example, wooduser houses, on average, are larger by 500 square feet than the nonwooduser houses. Also wooduser families are from 0.5 to 0.8 person larger. The data in Table 2.1 also support

*These self-reports were collected before weatherization, during the 1984 PNWRES survey.

Table 2.1 Demographic characteristics of woodusers and nonwoodusers by selected samples (means)

	Sample				
	All monitored homes	All wood-users	All nonwood-users	Wood channel households	Wood channel households -heavy woodusers[a]
(N)	(246)	(183)	(63)	(76)	(38)
Household income ($, 1982)	27,600	30,300***	19,700	28,100	28,200
Age of building (yrs)	21.1	20.3	23.3	21.9	23.6
House size (sq ft)[b]	1,440	1,570***	1,100	1,550	1,550
Household size (# persons)	2.9	3.1**	2.6	3.3	3.4
Owner occupiers (%)	92	96**	81	97	100
Length of residence (yrs)	9.9	9.6	10.7	8.8	9.4
Age of head (yrs)	48.5	46.1***	55.4	43.5	44.9
Education of head (yrs)	13.1	13.4	12.2	13.6	13.4
Age of primary heating system (yrs)	10.3	8.8***	14.8	7.5	5.9

[a]A heavy wooduser is a household that ranks above the median value of a ranking variable developed to measure the intensity of wood use in wooduser households. In developing the ranking variable, ordinal values were assigned to self-reports of primary and supplemental woodfuel use for space heating and to the number of cords burned during the 1983/84 heating season as follows: Primary woodfuel use = 10; supplemental woodfuel use = 5; 'cords' GT 7 = 14; 'cords' GT 5 and LE 7 = 10; 'cords' GT 3 and LE 5 = 6; 'cords' GT 2 and LE 3 = 4.

[b]All demographic characteristics were collected from the 1984 PNWRES survey. The house size variable was measured during the audit.

Mean value significantly different from all nonwoodusers at .05; * at .01.

earlier findings concerning heating equipment age: woodusing households have newer primary heating systems.

There are two additional insights derivable from Table 2.1 that are not found in previous wood use studies. One is related to house age. It was found earlier (Tonn and White 1986) that woodusers had older houses than households that heated primarily with electricity. These new data indicate that heavy woodusers have older houses than other woodusers, suggesting that wood use may be compensating for electric heating systems and energy-inefficient building shells.

A second finding is that the average income of woodusers is much higher than that of nonwoodusers. Previous findings were mixed: families that used wood had higher incomes than families that used no wood but, among woodusers, wood fuel appeared to be an inferior good. One speculation is that income is related to wood use through house size; that is, higher income households tend to purchase more living space and then in turn may use more wood to help keep heating bills down.

Among all households, the measure of association between wood use and income is moderate (Pearson correlation, rho is 0.28). The relationship between wood use and house size is somewhat stronger (rho = 0.39). Among households that use wood (the woodusers), the correlation between <u>intensity</u> of wood use and income is weak and negative (rho = -0.14). However, intensity of wood use and house size are not related. Furthermore, house size and income are more strongly correlated among woodusers than among electricity-only households (rho = 0.37 for woodusers and 0.28 for nonwoodusers).

In effect, the capability to burn wood is considered an integral feature of large houses, at least among higher-income households.

However, the intensity of wood use seems to depend on socioeconomic factors unrelated to house size, yet it is probably driven downward by factors related to income.

Another factor associated with wood use is home ownership. From Table 2.1 one can gather that a very high percentage of woodusers own their own homes. Possibly homeowners have more freedom to install wood burning equipment, more space to store wood, and have more economic incentives to invest in wood burning equipment than renters.

The relationship across demographic variables between woodusers and nonwoodusers in the HRCP is similar to the wooduser/nonwooduser relationship throughout the Bonneville service area. As indicated in Table 2.2, regional woodusers and nonwoodusers are different from one another, much like HRCP woodusers and nonwoodusers. Furthermore, the woodusers of HRCP resemble regional woodusers. In effect, the submetered wood channel houses reflect the regional demographic characteristics of woodusers.

2.2 CONSUMPTION OF WOOD IN TERMS OF CORDS

The information presented in Table 2.3 pertains to reported consumption of cords for the sample of submetered homes which completed the 1986 Wood Heating Survey. The data extend from the heating season of 1983/84 to the heating season of 1985/86. The earliest report of wood use was collected as part of the 1984 survey; the latter two reports come from the Wood Heating Survey. The three-year time span allows only a very rough estimate of wood use trends, but facilitates speculation about the effects of retrofit on wood use.

Table 2.2 Demographic characteristics of 1983 PNWRES households and wood channel households[a,b]

	HRCP[c]		PNWRES[d]		
	Wood Channel		Woodusers		Non-woodusers
(N)	(100)		(750,000)		(860,000)
Household income	27,700		26,900	***	17,100
Age of building (yrs)	22.4		24.4	***	21.0
House size (sq ft)[c]	1,520		1,600	***	1,050
Household size (# persons)	3.3		2.9	***	2.3
Homeowners (%)	93		81	***	46
Length of residence (yrs)	8.3	*	8.6	***	6.4
Age of head (yrs)	43.7		44.7	*	45.9
Education of head (yrs)	13.4		13.8	***	12.7
Age of primary heating system (yrs)	7.4		8.5		9.0

[a]Data are mean values.

[b]The 1983 PNWRES refers to the regional survey administered by Lou Harris, Inc., to 4703 stratified and randomly sampled residential energy customers in the Bonneville service area in 1983. Recall that this study refers to the 1984 PNWRES, which is the same 1983 PNWRES administered to the 320 HRCP submetered houses in 1984.

[c]The original 100 of 320 submetered houses before data quality screening.

[d]1983 PNWRES values are weighted. Values based upon data from houses with permanent electric space heating equipment.

*,**,***Indicates means to the immediate left and right are significantly different at .10; at .05; at .01.

With respect to trends, from 1983/84 to 1984/85, reported wood use was constant for the wood channel households that can be considered

Table 2.3 Annual wood use - cords (means)[a]

(N)	All woodusers (112)	Wood channel households (46)	Wood channel households-heavy woodusers (23)
Cords burned (1983/84)[b]	3.8	3.8	5.0
Cords burned (1984/85)[c]	3.9	3.9	5.0
Cords burned (1985/86)[c]	3.8	3.8	4.7

[a]Reported only for houses that completed 1986 Wood Heating Survey.

[b]The self-report of cords used during the 1983/84 heating season was collected during the 1984 PNWRES survey.

[c]The self-reports of cords used during the 1984/85 and 1985/86 seasons were collected during the 1986 Wood Heating Survey.

heavy woodusers, and increased slightly (3%) for the other samples. It is difficult to conclude that these increases indicate a trend toward individual households using more wood. One reason is that there are only two data points. Furthermore, data reported by Tonn and White (1986) show that average cords use per household between 1979 and 1983 has increased or decreased depending on the sample examined.*

The monitored houses were retrofit between the 1984/85 and 1985/86 heating seasons. The information presented in Table 2.3 indicates that

*This is not to say that wood use in the aggregate is not going up because it is: more houses are using wood. However, there is no consistent indication that individual households have increased the number of cords burned.

after retrofit, the number of cords consumed decreased by 6% for the heavy woodusers. If one assumes that the expected trend in wood use would be toward increases, then retrofit may be responsible for cutting wood consumption by an even higher percentage. Indeed, in Section 3 we report that retrofit appears to have saved a great deal more wood than electricity for the wood monitored homes.

The data presented in Table 2.3 must be reviewed cautiously. Respondent self-reports of cords consumed are not very reliable. Indeed, simple regression analysis of submetered wood stove energy output on reported cords does not indicate a satisfactory level of reliability (Table 2.4). The adjusted R^2s range from 0.12 to 0.15 for different

Table 2.4 Relationships between monitored wood use and survey reported cords (N = 46)[a,b]

Model	Dependent variable	Intercept	Independent variable	Adjusted R^2	Number Nonmissing Observations
1	Submetered wood kWh (1984/85)	2100	1015** (cords) (1984/85)	.14**	35
2	Submetered wood kWh (1984/85)	909	4041** LN (cords) (1984/85)	.14**	35
3	Submetered wood kWh (1985/86)	853	846** (cords) (1985/86)	.12**	37
4	Submetered wood kWh (1985/86)	-154	3338*** LN (cords) (1985/86)	.15***	37

[a]Reported for submetered houses with a 1986 Wood Heating Survey.

[b]LN represents natural logarithm.

**Significant at 0.05; ***Significant at 0.01.

specifications of the cords independent variable and the cords variable is only highly significant in one equation. Reasons for unreliability include:

- ignorance of how much wood is in a cord;
- no knowledge of how many cords are purchased because purchases are made by pickup truck loads;
- households that cut their own wood may never have occasion to think in terms of cords;
- the inability to keep track of what is used because backyard inventories change in imprecise and complex ways;
- BTU content of wood varies substantially by type of wood;
- wood stoves vary in efficiency; and
- individuals may operate wood stoves in ways that substantially affect efficiency.

2.3 WOODUSER ATTITUDES

Attitudes have the potential to significantly influence household behavior. For example, preferences related to the comfort of wood heat could overcome aversion to the manual labor involved with fueling wood burning equipment. This subsection presents summaries of attitudes about wood use drawn from the 1986 Wood Heating Survey. Another set of attitude questions is associated with the 1984 survey and is analyzed in Section 5 as part of the econometric exercises.

The Wood Heating Survey contained five questions pertaining to attitudes about wood use. The summaries presented in Table 2.5 are restricted to monitored homes. Because of a skip sequence in the survey, only households that use wood answered the attitude questions: comparisons to nonwoodusers are, unfortunately, not possible. However, to try to provide some interesting viewpoints on the data, summaries are

Table 2.5 Attitudes related to wood use (%)[a,b,c]

Question	Strongly Agree	Agree	Neutral	Dis-agree	Strongly disagree	Don't know
Wood is less expensive	54/46	27/41	18/9	0/0	0/0	1/5
Wood provides more comfort	44/40	28/29	23/19	3/6	1/2	1/4
Wood is readily available	32/30	32/37	22/24	11/6	1/0	1/4
Burn wood for appearance rather than heat	4/2	8/2	7/15	36/34	44/43	1/4
Use wood to cut fuel costs	66/64	25/25	5/6	1/2	1/0	1/4

[a]The number to the left of the slash mark relates to woodusers with the water heating monitors; the number to the right relates to woodusers with the wood heating monitors.

[b]Reported only for woodusers that completed the 1986 wood heating survey (N = 112).

[c]Likert-based; 1 = strongly agree,...,5 = strongly disagree.

presented for both wooduser households with water heating channels and for the wood monitor households.

Four firm conclusions can be drawn from the data presented in Table 2.5. First, there are no large differences in the attitudes between the water heating and wood channel households. Second, wood use appears to be economically driven.* Overwhelmingly, wood is judged as

*This and the following two findings must be viewed as post hoc justifications by households that already use wood.

being less expensive and is used to cut overall fuel costs. In addition, wood is not used for aesthetic reasons. These attitudes support the contention that wood is an inferior good--i.e., either as real household incomes increase or as competing fuel prices decrease, residential wood use will decrease.

Third, wood appears to have additional appeal in that it provides more comfortable heat than other fuels, although this appears to contradict the inferior fuel contention. It is possible, though, that this positive attribute of wood heating would not have been so strong had the negative attributes concerning convenience and cleanliness been queried. Fourth, most respondents consider wood to be readily available in the Pacific Northwest, an attitude which promotes serious consideration of wood use.

In summary, woodusers have very positive attitudes toward wood use for space heating. These are derived first from economic advantages of using wood, and secondly, from home comfort.

2.4 TYPES OF WOOD USED

Wood use analysis is complicated by the choice of which wood to burn. Electricity users consume generic kWh and natural gas users burn a standard product, but woodusers can burn wood that varies by heating quality, splitting difficulty, starting characteristics, and spark production (PP&L 1981). A series of questions on the 1986 survey permits some analysis of strategies taken in using the various types of wood. The results are again presented by water heating channel and wood channel households (Table 2.6).

Table 2.6 Types of wood used by households (%)[a,b]

	Main Type	Supplemental type 1	Supplemental type 2
Alder	21/22	0/0	0/0
Fir/Hemlock	61/62	18/18	0/0
Maple	1/0	13/6	7/6
Oak	7/4	21/35	17/13
Pine	1/0	6/4	7/7
Cherry	1/2	1/0	1/2
Apple	1/2	10/7	7/7
Tamarack	0/0	7/4	8/9
Other	0/0	5/2	6/11
N/A	6/9	19/26	46/46

[a]The number to the left of the slash mark relates to woodusers on the water heating monitors; the number to the right relates to woodusers with the wood heating monitors.

[b]Reported only for woodusers that completed the 1986 Wood Heating Survey (N = 112).

Once, again, the water heating and wood channel households show no large differences in responses. A more interesting observation is that relatively poor heating quality wood (alder and fir/hemlock) dominate as the main types of wood burned. These woods are easy to split and start but produce a fair amount of sparks. Another interesting observation is that high-quality woods are the favorite supplemental types (maple and oak). It is possible that high-quality wood is saved for certain occasions, which could be as frequent as every evening or as infrequent as only on weekends. It is also possible that heavy woodusers prefer large quantities of cheaper types of wood. Those who use it only occasionally are willing to buy the higher quality wood.

3. ELECTRICITY DISPLACEMENT BY WOOD

This section scrutinizes the effects that the Hood River Conservation Project has had on wood use in the monitored homes, and attempts to reach conclusions about how much electricity wood use displaces. These are important tasks, if only because the submetered wood and electricity space heat channel data are unique. As we shall see, at least for the samples relevant to this study, wood is a very important element in the space heating equation.

Similar to Section 2, multiple viewpoints to understanding wood and electricity consumption are explored. The first relies on analysis of traditional normalized annual consumption (NAC) averages taken from billing histories and weather data. Next, averages taken over the submetered data are presented, providing valuable information on space heat and kWh savings. A third view analyzes correlations between savings measures and retrofit costs and predicted savings, mainly to explain changes in wood and electricity consumption and how they are related. The fourth viewpoint, which may be the most interesting, assesses measures of retrofit effectiveness and finds that retrofit investments in heavy wooduser households may have been well spent.

3.1 ANALYSIS OF NORMALIZED ANNUAL CONSUMPTION DATA

Traditionally, analysis of the effectiveness of residential energy conservation programs has been based on normalized annual consumption methods. The standard method uses long-run weather data, short-run weather data, and electricity bills (or other fuel bills) to calculate electricity consumption that would have occurred over a year of average temperatures. The method works best when only one fuel is used for space heating and other household uses. Concerns arise over the reliability of the method when households use multiple fuels. Interpretations of parameter estimates related to baseload and space heating coefficients become problematic as R^2s decrease and standard errors increase. The NAC estimate itself, however, is nearly as robust in multiple fuel houses as in single fuel houses (Fels, 1986).

The data presented in Table 3.1 represent four years of NAC values for both wood using and nonwoodusing households among the monitored

Table 3.1 Normalized annual consumption (NAC) of electricity by monitored homes, 1982-1986 (kWh)

(N)	All moni-tored homes (239)	All wood users (177)	All non-woodusers (62)	Wood channel households (76)	Wood channel households heavy woodusers (38)
NAC 1982/83	20,800	20,600	21,300	20,000	18,600
NAC 1983/84	20,300	20,200	20,600	19,300	17,400
NAC 1984/85	19,800	19,500	20,500	18,600	16,700
NAC 1985/86	17,700	17,600	17,900	17,400	16,200
DNAC (1982/83 -83/84)	490	410	670	670	1,140
DNAC (1983/84 -84/85)	510	640	120	1,080	710
DNAC (1984/85 -85/86)	2,070	1,870	2,630	1,190	570
Total DNAC (1982/83 -85/86)	3,070	2,920	3,420	2,940	2,420

houses. In general, expected patterns emerge. The NACs decrease over time as the direct result of retrofit, and nonwoodusers tend to use more electricity than woodusers. There are some unexpected patterns, however.

For example, in the 1982/83 year, nonwoodusers did not use much more electricity than the woodusers (3% more; Table 3.1). One might have expected that woodusers would use much less electricity even though the woodusing houses are considerably larger (by 41%; Table 2.1) than the nonwoodusing houses. Another interesting observation relates to the changes in NACs between 1982/83 and 1985/86. As expected, the non-woodusers register large decreases in electricity but what should one expect to find with the woodusers? Given almost identical 1982/83 base levels, one might expect to find equal savings across the board for all samples of woodusers. In fact, not even the heavy woodusers possess NAC changes comparable to the nonwoodusers. The typical wooduser savings are 15% less than the nonwooduser savings, meaning that it is possible that wooduser households increased the proportion of electricity to wood heat after retrofit. This finding is consistent with the theory of wood as an inferior good because a drop in electricity bills, with other costs remaining constant, increases real household income.

This explanation is somewhat tempered by the fact that over 75% of those households that answered the 1986 survey and use wood stated that in the future they would maintain the same level of wood use. Less than 7% said that they would reduce wood use. Unfortunately, this question was asked after, not before, retrofit which means that households had already adjusted their wood use. However, after reducing wood use after retrofit, woodusers may increase wood use and reduce electricity demand in the next few years to reestablish the preretrofit wood/electricity ratios.

3.2 ANALYSIS OF SUBMETERED DATA

Annual seasonal summaries of the submetered data are presented in Table 3.2.*,** The data represent averages for both the electricity space heating channel and the wood heat channel for both woodusers and nonwoodusers. In reviewing and interpreting the wood kWh equivalent results, two points must be considered. First, there are uncertainties associated with measuring stove heat outputs. (Refer to Section 1.1 and Appendix A for discussions.) Second, reported are only savings in wood heat output. Corrections made for wood stove efficiency, which range from 40 to 70%, would be required to determine total wood energy savings.

Table 3.2 offers four interesting findings about electricity displacement by wood. First, in woodusing homes, the energy provided by wood is between 1.7 (1985/86) to 4.5 (1984/85) times as much as the electrical energy used for space heating. The former figure is

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*Since the primary concern is with wood and electricity used for space heating, "seasonal" summaries of submetered enduses were computed. The season of 1984/85 began on 10/14/84, when average daily temperatures fell regularly to below 60 °F, and ended on 4/2/85 when average temperatures increased to 60 °F or more on a regular basis. Similarly, the 1985/86 season began on 10/17/85 and ended on 3/30/86. This approach also had the fortuitous consequence of avoiding difficult decisions concerning missing submetered and incomprehensible data. Unfortunately, this approach precludes direct comparison between NAC results and submetered summaries, and does eliminate some days when wood is used, even during the summer months.

**Daily energy use was not weather-adjusted. The 12-month season of 1985/86 was only 4% colder than 1984/85 and approximately 12% colder than the 30-year normal.

Table 3.2 Submetered use of wood and electricity by monitored homes, 1984-86 (kWh)[a]

	(N)	All monitored homes (246)	All non-wood-users (63)	Wood channel households (76)	Wood Channel households -heavy woodusers (38)
Electric Space (1984/85)		5,830	8,590	3,530	1,810
Electric Space (1985/86)		4,410	6,840	2,770	1,610
Wood (1984/85)		1,980[b]	-	6,680	8,100
Wood (1985/86)		1,430[b]	-	4,820	5,710
Electric space savings		1,340	1,760	610	200
Wood space savings		550[b]	0	1,920	2,490
Total space savings		1,890	1,760	2,530	2,690

[a]See Appendix A for a discussion of the submetered data and the basis for presenting data from the wood heating channel in kWh.

[b]Average over all 246 households whether or not wood was used or measured by submeter. The calculated value is energy; the actual volume of wood saved is not known.

associated with all wood channel households, the latter with heavy woodusers. At least in the wood channel homes, wood is by far the dominant space heating fuel.

Second, wood burning households used nearly 20% more energy in total for space heating (1984/85) than households that did not burn wood. Again, this can be explained by the fact that the wood using houses are larger, and available labor may be greater because of larger family sizes. Third, woodusers saved between 3.1 and 12.5 times more wood energy than electrical energy for space heating. This means that the HRCP has saved a great deal of wood as well as electricity. Lastly, as discussed above, the woodusers saved a great deal more energy for space heating--53% more, distributed across wood and electricity savings--than the nonwoodusers.

3.3 RELATIONSHIPS BETWEEN ENERGY SAVINGS AND RETROFIT VARIABLES

Data presented in the previous subsection indicate that wood accounts for nearly two-thirds of the average wood channel home's total space heat energy. In this subsection, data are presented which provide insights into how measures of actual energy savings relate to retrofit costs and predicted savings. The goals are to explore relationships between wood and electrical energy savings, and between predicted retrofit savings and actual savings.

The results in Table 3.3 offer mostly expected relationships. For example, change in normalized annual consumption (DNAC) is positively related to change in monitored kWh for electricity space heat and total kWh, and is similarly correlated to change in retrofit costs and predicted savings. Monitored electricity kWh changes are also positively related to costs and predicted savings. In addition, costs and predicted savings are highly correlated, which indicates at the very least a strong internal consistency in this sample in the implementation of HRCP.

Unexpected results are associated with changes in wood stove heat output. First, such changes are usually negatively related to DNAC,

Table 3.3 Pearson correlations between actual energy savings, retrofit costs, and audit estimates of savings (N = 76)

	A	B	C	D	E	F
A. DNAC (kWh) (1984/85 -85/86)	-	-.05	.30***	.35***	.35***	.39***
B. Monitored wood (kWh) (1984/85 -85/86)		-	-.21*	-.16	.03	.19
C. Monitored electricity space (kWh) (1984/85 -85/86)			-	.83***	.25**	.31***
D. Total monitored electricity (kWh) (1984/85 -85/86)				-	.38***	.46***
E. Retrofit cost ($)					-	.78***
F. Predicted electricity savings (kWh)						-

*Significant at .10 level; **Significant at .05 level; ***Significant at .01 level.

changes in monitored electricity space heating, and total electricity consumption. These observations indicate that retrofits did not reduce electricity and wood consumption proportionally. Instead, either wood use was reduced greatly, while electricity was reduced only minimally, or electricity was reduced greatly and wood use only minimally. Given the results from Table 3.2, it can be argued that, in most cases, wood use was reduced much more than electricity. In other words, electricity is displacing wood use.

Second, changes in wood stove heat output are unrelated to retrofit costs and predicted savings. This is a difficult observation to explain because data presented thus far indicate that wood use declined after retrofit. The only plausible explanation developed at this time is that household behavior with respect to wood use varied greatly after retrofit.

3.4 RETROFIT EFFECTIVENESS

This subsection addresses the effectiveness of the HRCP retrofits with respect to woodusers. The _a priori_ assumption was that, in all likelihood, dollars spent on retrofit measures installed in wooduser houses would not be as cost-effective in saving electricity as dollars spent in nonwooduser houses. To gather empirical evidence to support this hypothesis, retrofit costs, predicted savings, and actual savings for wood using and other households are analyzed while controlling for the size of the house. The data presented in Table 3.4 basically support the assumption. It appears that with respect to saving energy the best investments were made in heavy woodusing houses, and with respect to saving electricity, the best investments were made in nonwoodusing households.

To build up to this conclusion in a rigorous fashion, houses which appeared most in need of retrofit are examined first. Table 3.4 shows that (row 2) heavy woodusers needed the most retrofit, and eventually installed the most comprehensive retrofit packages (row 3). In comparison, the nonwoodusers had the least potential savings and installed the least comprehensive retrofit packages. However, when controlling for

Table 3.4 Measures of retrofit effectiveness

		All monitored homes	All wood-users	All nonwood-users	Wood channel households	Wood channel households -heavy woodusers
	N	(246)	(183)	(63)	(76)	(38)
(1)	House size (ft^2)	1,400	1,570	1,100	1,550	1,550
(2)	Recommended retrofit savings (est. kWh/yr)	7.430	8,020	5,770	8,340	8,440
(3)	Installed retrofit savings (est. kWh/yr)	6,640	7,210	4,990	7,190	7,640
(4)	Retrofit Cost ($)	4,650	5,050	3,490	5,040	5,290
(5)	Recommend retrofit savings per ft^2 (2)/(1)[a]	5.2	5.1	5.2	5.4	5.4
(6)	Installed retrofit savings per ft^2 (3)/(1)	4.6	4.6	4.5	4.6	4.9
(7)	Retrofit cost per kWh per ft^2 (4)/(3)/(1)[b]	4.86	4.46	6.4	4.52	4.47
(8)	Monitored total space heat savings (kWh/yr)[c]	1,890	1,930	1,760	2,530	2,690
(9)	Savings over predicted savings (%) (8)/(3)	28	27	35	35	35
(10)	Cost per kWh saved per ft^2 (4)/(8)/(1)[b]	17.09	6.67	18.03	12.85	12.69
(11)	Monitored electric space heat savings	1,340	1,200	1,760	610	200
(12)	Cost per electric kWh saved per ft^2 (4)/(11)(1)[b]	24.10	16.80	18.03	53.31	174.64

[a](2)/(1) means row (2) divided by row (1).

[b]For readability and ease of comparison, quotients were multiplied by 10,000.

[c]Sum of electric and wood space heat savings.

house size, nonwooduser retrofit needs closely matched the needs of the heavy woodusers (row 5).

Row 6 indicates the magnitude of the installed retrofit package controlling for house size. The numbers indicate that the heavy woodusers installed relatively more conservation measures than all the other samples and that all the other samples installed about equal amounts of conservation. Clearly, the heavy woodusers took full advantage of the provisions of HRCP. This observation fits well with an observation made by Tonn and White (1986) that households perceiving the need to save money on space heating tended either to use wood or to participate in conservation programs.

In reviewing the numbers in row 7, one can see that based on predicted savings, the investments in the heavy woodusing houses were projected to be relatively cost-efficient with respect to saving electric kWh. That is, fewer dollars were to be spent to save electricity for space heating, controlling for house size, than on other samples. In fact, using this measure, the most inefficient investments were expected to be made in the households that didn't use wood. Reasons for these observations are not readily apparent, except that the heat loss methodology used to prepare the estimates did not factor in wood use.

Row 10 indicates that with respect to saving electricity and wood energy for space heat, the best investments were made in the wood burning houses and the least effective investments were made in the nonwoodusing houses. Of course, much of the energy saved relates to wood and not electricity but if and when these houses stop using wood, then the full effectiveness of the conservation measures would be felt. Probably the most important finding is that when electricity savings alone are analyzed, the investments made in the woodusing houses are considerably more expensive for each electric kWh saved than the investments in the nonwoodusing houses (Table 3.4, row 12). These results demonstrate, at least for this small sample of houses, that wood use affects the economic efficiency of investments made in the HRCP in two ways: (1) conservation in woodusing households is an expensive alternative to saving electricity in electrically-heated houses, and (2) HRCP reduced wood consumption and thus minimized the potential displacement of electricity by wood. This latter point is important because in the future, potential swings in electricity consumption due to changes in wood consumption will be smaller, which poses less uncertainty for Bonneville power system planners. This reduction in uncertainty is also valuable because the contribution of electrically-heated homes to system peak demands was almost twice that of wood-heated homes (Stovall, 1987).

4. WOOD USE PATTERNS

The 15-minute submetered data offer the opportunity to explore daily patterns of wood use in conjunction with daily patterns of electricity use for space heating. Rigorous analysis can answer questions about the number and nature of the most common wood/electricity patterns, whether patterns are more or less prevalent on certain days of the week, whether outdoor temperatures are related to indoor temperature patterns, and what types of households choose which sets of patterns. This last piece of information could be useful in marketing of electricity. The approach used below groups daily wood/electricity patterns into clusters using cluster analysis procedures found in SAS (1985). The cluster approach is used because we had no firm, preconceived notions about the nature or number of important electricity/wood use patterns.

4.1 ANALYSIS OF AGGREGATE DAILY ENERGY USE PATTERNS

The first step in the pattern analysis was to decide what data could be analyzed. Cluster analysis could not be used with all of the 15-minute data because of computer size limitations. A series of decisions, described in the next few paragraphs, were made to reduce the amount of data. The resulting data set was used in the aggregate pattern analyses presented in this subsection as well as in the cluster analyses.

The first data reduction decision pertains to the aggregation of the data to compose the daily patterns. For a twenty-four hour period, 15-minute intervals could have been used, which would have resulted in 192 data points for each day (i.e., 96 for wood and 96 for electricity) for each observation and a total of 10 million observations. A 60-minute interval was chosen for two reasons: it may better represent the time frames over which households may make decisions to change space heating behavior (15 minutes seems too short); and Bonneville Conservation/Load/Resource Planning models typically use 60-minute intervals (Tonn et al., 1985). This decision reduced the size of the data set by a factor of four.

A second decision concerns how many days of the year to include in the pattern analysis. A first cut eliminated days between mid-March to mid-October as being unrepresentative of days requiring wood and electric heating. A second cut entailed choosing five representative seven-day weeks for each of the two heating seasons, seventy days in all. The weeks were matched between the seasons and included a range of typical outdoor temperatures. No week contained holidays so no complicated variations were introduced into the pattern analysis. These cuts resulted in a database with approximately 5000 observations, with each wood channel house accounting for approximately 70 observations, where each observation represents one day of data.

Figure 4.1 presents graphs describing daily patterns of monitored wood and electrical energy for space heating and monitored indoor temperatures averaged over all days and all households but split by pre- and postretrofit years. In 1984/85, wood stove output peaked between 8:00 a.m. and 10:00 a.m. and again between 7:00 p.m. to 9:00 p.m. Electricity use also peaked around 8:00 a.m. and then fell to a lower level the rest of the day. The 1985/86 pattern changed only slightly from the year before; the evening wood peak is less pronounced and a small evening electricity peak appears. In general, wood-use behavior changed more than electricity use behavior.

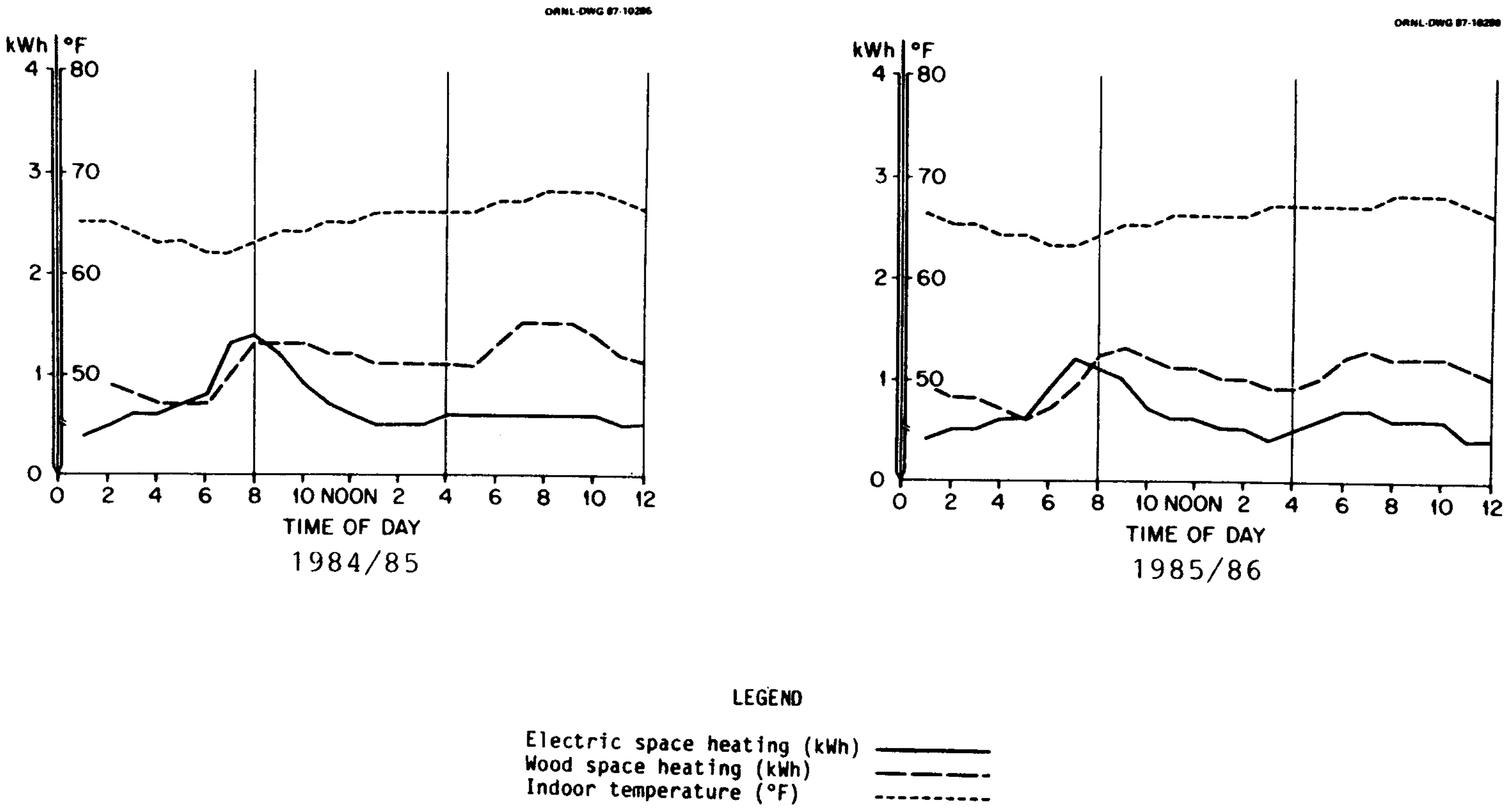

Fig. 4.1 Electric space heating (kWh), wood space heating (kWh), and indoor temperatures (°F), averaged over all households, by year.

Figures 4.2 and 4.3 present the 1984/85 and 1985/86 data broken down by four days of the week: Tuesday, Friday, Saturday and Sunday. The other weekdays are not presented because of their similarity to the two weekdays illustrated.

Each day is characterized by morning wood and electricity use peaks of approximately similar magnitude around 8:00 a.m. On Saturday and Sunday, electricity use declines after 8:00 a.m. and remains at a steady state for the remainder of the day. Wood use after 8:00 a.m. remains high and exhibits a small evening peak. In contrast, weekday wood use declines after 8:00 a.m. and peaks again in the evening. Electricity use also declines on these days and shows only a very small evening peak. The only noticeable difference between the weekdays and weekend days is the mid-afternoon wood use. This can be explained by the greater probability of people being home on weekend days to maintain wood burning operations.

The 1985/86 patterns differ only in small ways from the 1984/85 patterns. The evening wood peaks are less pronounced and the evening electricity peaks are slightly more pronounced. Evidently, retrofits have led to low wood use in the evening and relatively more electricity use. Weatherization has also made the 1985/86 patterns more similar to each other, so much so that one could not argue that patterns vary noticeably by day of the week. However, as is found in the next sections, the patterns hide interesting variations in pattern choices across households.

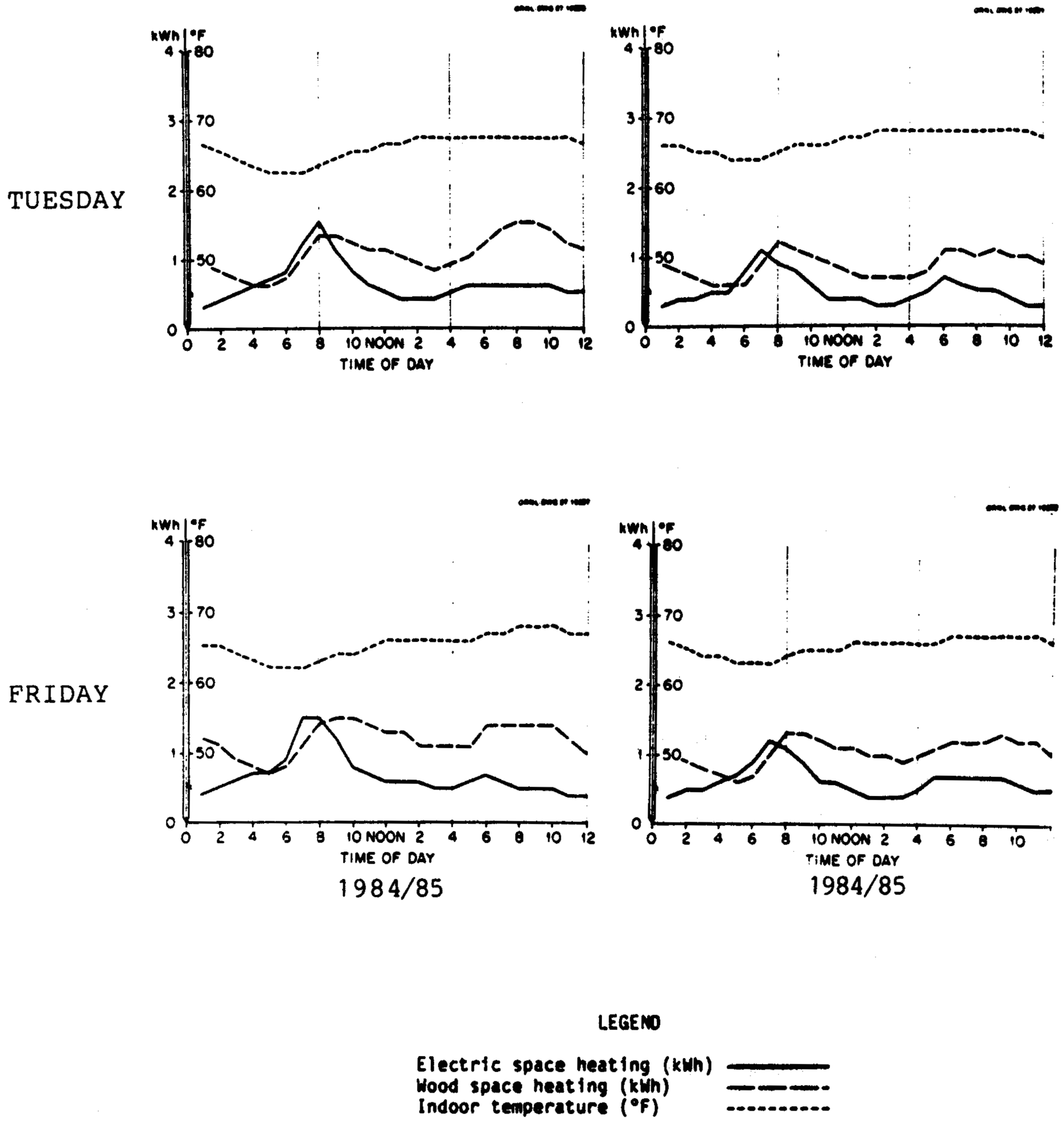

Fig. 4.2 Average electric space heating (kWh), wood space heating (kWh), and indoor temperature (^{o}F) by weekday (Tuesday and Friday), by year.

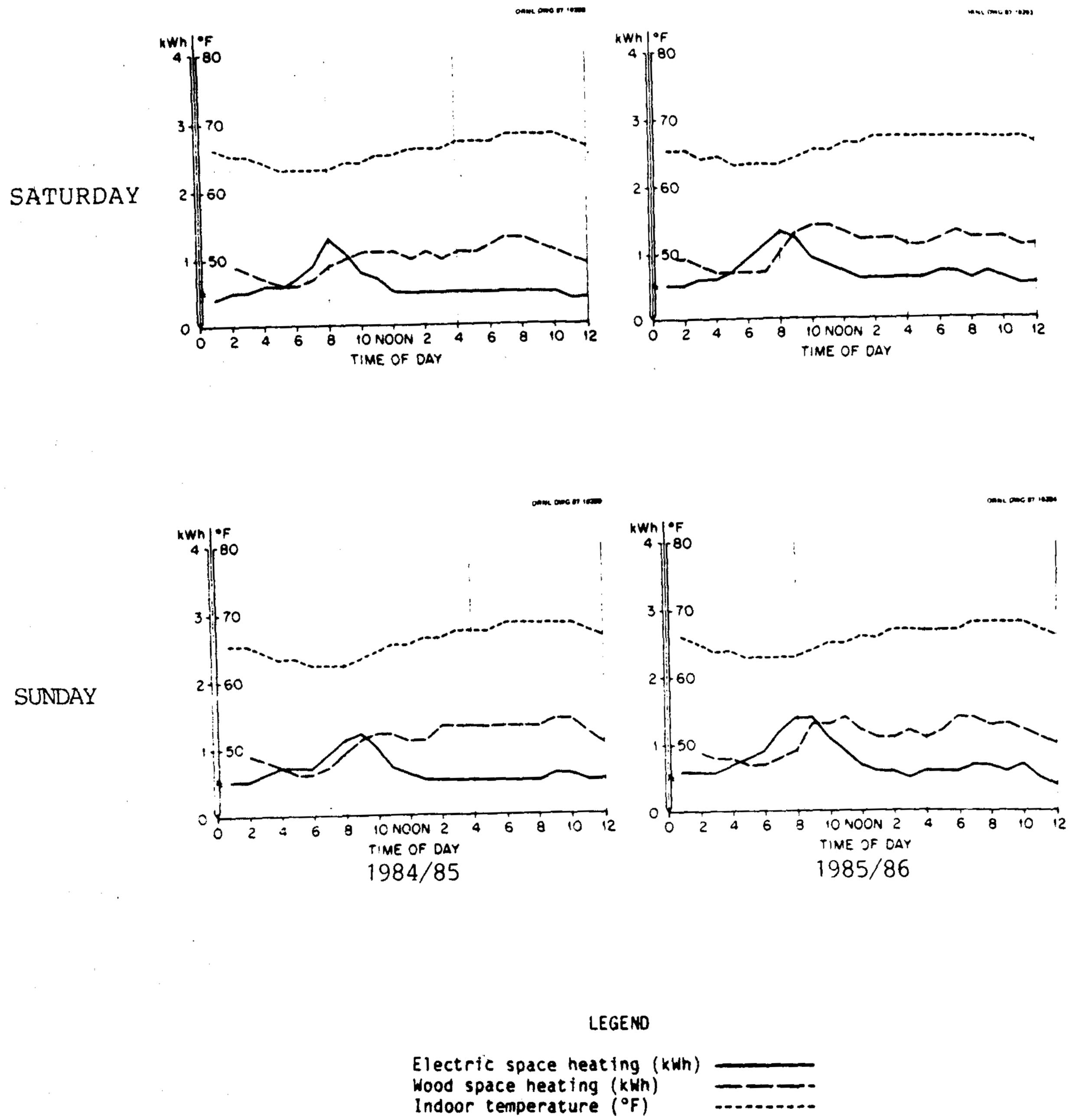

Fig. 4.3 Average electric space heating (kWh), wood space heating (kWh), and indoor temperature (°F) by weekend day (Saturday and Sunday), by year.

4.2 DAILY PATTERN CLUSTER ANALYSIS

This subsection explores the range of daily energy use patterns chosen by households pre- and postretrofit. The statistical approach used is cluster analysis. It was originally developed to facilitate the clustering of living organisms into species, etc. and has since been applied to a large number of problems. Issues surrounding the choice of clustering methodology are discussed before the results are presented.

The first problem was to choose the appropriate cluster methodology. PROC CLUSTER in SAS has numerous options, depending on the clustering criteria specified, the number of observations, and the number of clusters expected. The preferable approach is to choose a method that reports how clusters are constructed (e.g., Ward's Method) because the associated outputs indicate which clusters joined with other clusters at certain points in the analysis. Unfortunately, even with 2500 observations for a cluster run, the data processing requirements were too extreme for the preferred approach. The FASTCLUS procedure was used, which is recommended for data sets with 100 to 100,000 observations.*

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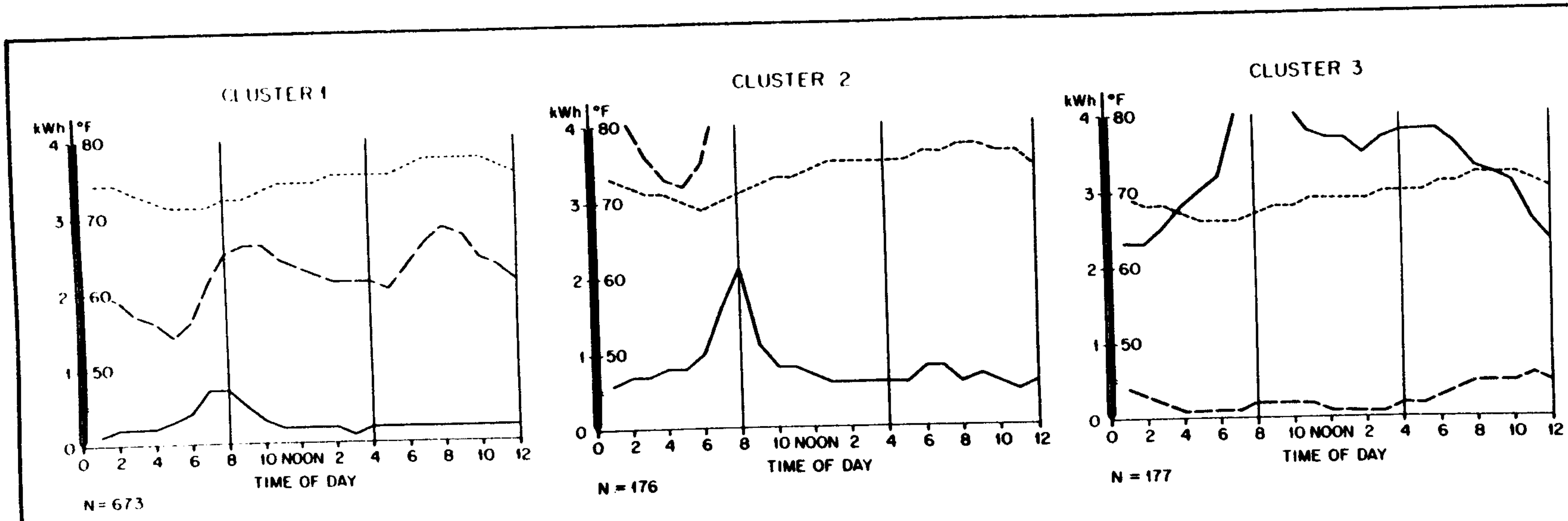
*FASTCLUS increases data processing efficiencies because the number of clusters into which the observations are grouped are prespecified. It uses the standard methods for clustering which entail minimizing the variance between (1) the mean of a variable over the observations in a cluster and (2) the observed values of the variable over the observations in a cluster. The smaller the average sum of variances in each cluster, the better will be the cluster results. In this application, 48 cluster variables were specified, 24 each for wood and electricity kWh for space heating for each of the 70 days per house (also called house-days). One variable represents the total kWh for that fuel in a one-hour period. For example, wood variable number eight represents the kWh produced by wood between 7:00 a.m. and 8:00 a.m. The FASTCLUS procedure, then, will place observations in clusters in such a way as to minimize the difference between the means of the 48 variables in a cluster and the observed values of the 48 variables associated with the observations in a cluster.

A second issue concerns how many clusters to use. A problem with FASTCLUS is that it gives undue weight to outliers. In early runs, many clusters emerged that had only one or two observations in them and few clusters contained significant numbers of observations. A priori expectations were that there would be around four to six noticeably different, but prominently chosen, patterns. The number of clusters was increased from 6 to 8 to 16 and finally to 24 until a reasonable set of significant patterns was found.

For both the pre- and postretrofit samples, five significant clusters were identified. Each contained over 100 observations, with the largest cluster containing 1229 observations.* Figure 4.4 contains graphs of the patterns of the mean values for the 48 variables for the five clusters found in the preretrofit data set. Figure 4.5 reports the same for the postretrofit data set. Average indoor temperatures as measured by the indoor temperature submeters are also plotted on the graphs. Table 4.1 contains general descriptions of each cluster and reports the frequencies.

The descriptions of the significant clusters are not unexpected. For each heating season, the set of clusters contains clusters with low wood and moderate-to-high electricity use, high wood use and low electricity use, low wood use and low electricity use, and patterns in between. Some difference is noted in the peaks for the cluster patterns, with some clusters having only morning electricity peaks and others having only evening wood peaks. In general, there is nothing surprising about the peaking patterns.

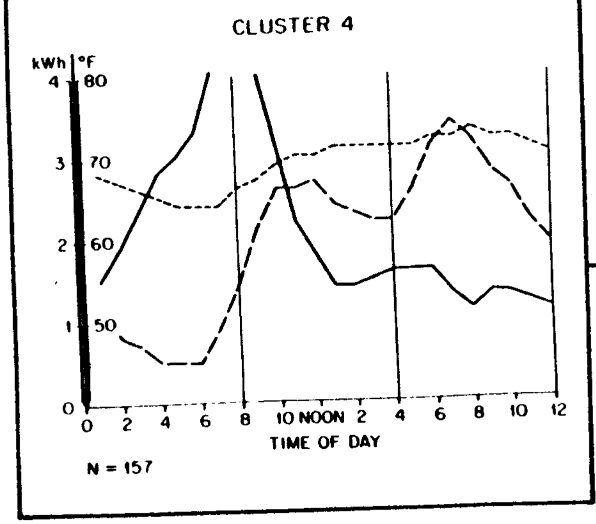
*Each observation contains 48 variables, 24 hourly wood kWh variables and 24 hourly electricity kWh variables, representing one day of space heating use for one household.



LEGEND

Electric space heating (kWh)
Wood space heating (kWh)
Indoor temperature (°F)

Clusters selected by SAS procedure FASTCLUS, and based upon hourly electric and wood space heating consumption for 2,615 house days.



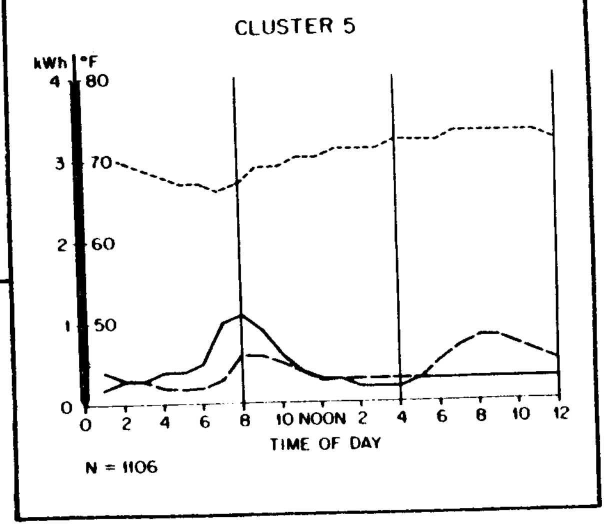
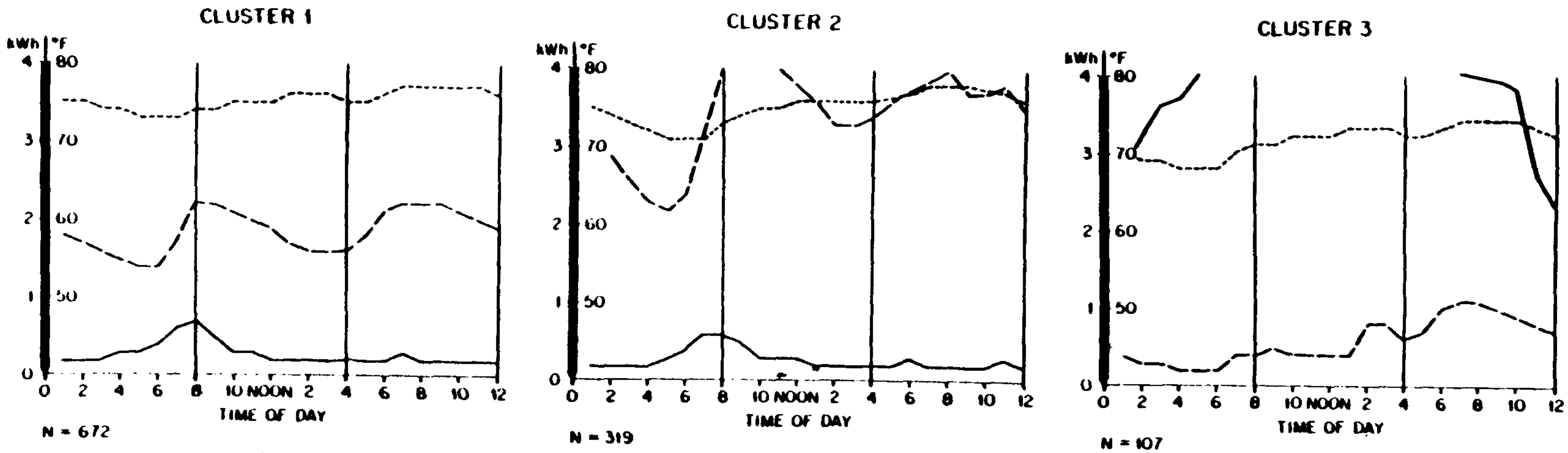
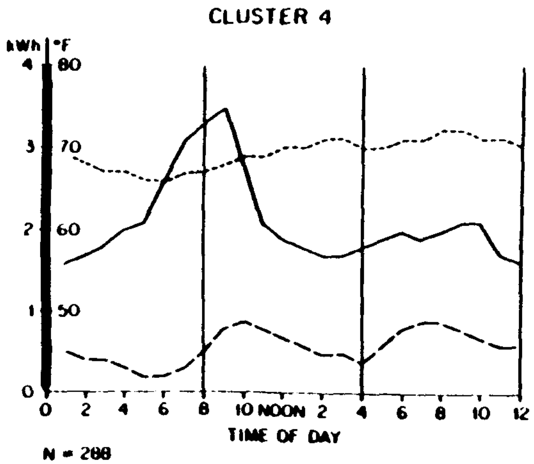


Fig. 4.4 Cluster mean values for 48 cluster variables and indoor temperature for the 1984/85 heating season, 10/14/84 through 4/2/85.





LEGEND

Electric space heating (kWh) ————
Wood space heating (kWh) — — — —
Indoor temperature (°F) ----------

Clusters selected by SAS procedure FASTCLUS, and based upon hourly electric and wood space heating consumption for 2,615 house days.

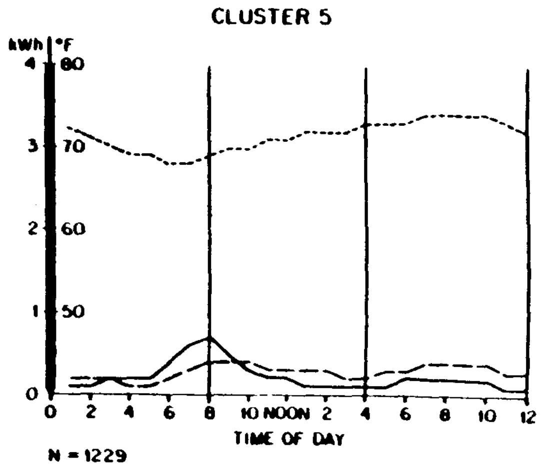


Fig. 4.5. Cluster mean values for 48 cluster variables and indoor temperature for the 1985/86 heating season, 10/17/85 through 3/30/86.

Table 4.1 Cluster analysis of actual electric and wood space heating submeter values, by house, by day (N = 4904)[a]

	Cluster Number	Frequency (house-days)	Description
Pre-retrofit	1	673	Moderate wood use, low electricity use, warm indoor temperature, common peaks
	2	176	High wood use, moderately low electricity use, warm indoor temperature, all day wood peak, morning electricity peak
	3	177	Low wood use, high electricity use, cool indoor temperature, all day electricity peak,
	4	157	Moderate wood use, moderate electricity use, cool indoor temperature, morning electric peak, afternoon and evening wood peaks
	5	1106	Low wood use, low electricity use, cool indoor temperature, morning electricity peak, morning and evening wood peaks
Post-retrofit	1	672	Moderate wood use, low electricity use, very warm indoor temperature, common peaks
	2	319	High wood use, low electricity use, very warm indoor temperature, common peaks
electric	3	107	High electricity, moderately low wood use, moderate indoor temperature, all day peak, evening wood peak
	4	288	Low wood use, moderate electricity use, cool indoor temperature, common peaks
	5	1229	Low wood use, low electricity use, moderate indoor temperature, morning electricity and wood peaks

[a]Electric and wood space heating submeter values were represented in arrays from 1 to 24 in each of the 4904 observations. The number of observations is less than 4904 because clusters with small frequencies are not reported.

More interesting observations emanate from the frequency counts and descriptions of indoor temperatures. With respect to frequency counts, one cluster in each year is much larger than the others and the size of the clusters virtually maps from one year to the next. For example, in two clusters labeled "1," there are approximately 670 observations and the patterns are virtually the same. The only significant difference is that in the 1985/86 heating season there were more high wood use/low electricity use days and much less low wood use/high electricity use days. There were also more low wood use/moderate electricity use days, which is most likely due to the retrofits. Indeed, all the patterns in 1985/86 use less energy than the similar patterns in 1984/85.

Another effect of retrofit is the general rise in indoor temperatures. For all submetered houses, indoor temperature increased by more than 0.4^{o}F after weatherization. Although woodusers typically maintain higher indoor temperatures, this average increase appears to be unrelated to wood use among households in this study.

Most patterns in 1985/86 have temperature patterns that, very roughly speaking, are one notch higher than in 1984/85. For example, whereas the temperatures in cluster 1 for 1984/85 could be described as warm, the temperatures in the corresponding cluster in 1985/86 could be described as very warm. In summary, while the patterns between the heating seasons appear stable, there was some shift in the types of patterns used by the households, the energy related to the 1985/86 patterns is lower, and the indoor temperatures in the postretrofit year are higher. (See also Dinan, 1987).

4.3 ANALYSIS OF DAILY PATTERN CLUSTERS

The second step in the pattern analysis is to understand pattern variations over days of the week and outdoor temperature extremes. To accomplish this task, each observation used in the cluster analysis was assigned a cluster number (Table 4.1), and the day of the week of the observation was identified. Then a frequency of the cluster variable by the seven days of the week was performed. The results are contained in Tables 4.2 and 4.3, respectively, for the two heating seasons.

Similar to the results presented in Section 4.1, there are no noticeable patterns to be found in the data; the observations spread

Table 4.2 Cluster frequencies on day of week, 1984/85 heating season (N = 2289)[a]

Day of week	Cluster 1	2	3	4	5
Sunday	14.7	12.4	10.8	10.2	14.2
Monday	15.9	12.4	10.2	10.8	13.7
Tuesday	12.0	11.9	13.1	16.6	15.1
Wednesday	11.7	13.6	18.8	14.7	14.0
Thursday	18.1	22.0	19.9	21.7	14.7
Friday	14.6	11.9	15.3	15.3	13.1
Saturday	12.9	15.8	11.9	10.8	15.2
Total	100.0	100.0	100.0	100.0	100.0
Cluster size (house days)	673	177	176	157	1106

[a]Reported are column percentages.

Table 4.3 Cluster frequencies on day of week, 1985/86 heating season (N = 2615)[a]

Day of week	Cluster 1	2	3	4	5
Sunday	12.4	14.1	20.6	18.1	13.5
Monday	17.4	13.5	7.5	18.8	12.4
Tuesday	13.4	12.9	8.4	12.9	16.3
Wednesday	12.9	14.7	12.2	14.6	15.4
Thursday	14.4	14.4	13.1	11.5	14.9
Friday	13.8	15.7	16.8	11.8	14.3
Saturday	15.6	14.7	21.5	12.5	13.3
Total	100.0	100.0	100.0	100.0	100.0
Cluster size (house days)	672	319	107	288	1229

[a]Reported are column percentages

fairly evenly over the seven days. For example, for cluster 1 in the 84/85 heating season, a low of eleven percent of the days fall on a Wednesday and a high of eighteen percent fall on a Thursday. A pattern that might indicate a variation of patterns by day of week, on the other hand, might have resulted in over fifty percent of the days on Saturday and Sunday, for example. For cluster 3 in the 1985/86 heating season, this type of condition is approached but is not close enough in our judgment to corstitute a reliable finding.

The implication of these findings is that some other variables drive the pattern differences. Analysis of patterns by weather does provide significant results but explanations of how the analysis was conducted must first be presented.

The first step was to rank in order the 70 days used in the cluster analysis by average temperatures. Next the 10 coldest days, 10 warmest days, and 20 average temperature days were identified. Third, matched days between the heating seasons were chosen from the three groups of days. In the coldest day category, the two days, one for each heating season, were chosen from November and December, when the average outdoor temperatures were 8 and 10°F, respectively. The warmest days came from March and were 57 and 58°F. The average days came from October and November and were 32 and 35°F. Care was taken to match comparable weekdays (e.g., a Tuesday and a Wednesday).

Table 4.4 presents the results of a frequency analysis on the cluster variable by the three temperature categories from coldest to warmest, notated as BRRR, COLD and MILD. The most noticeable observation is that over 90 percent of the MILD observations fall into the number 5 clusters, which represent low wood use/low electricity use days. As temperatures drop, the patterns begin to diffuse among the other clusters. On COLD days, wood is mostly used to meet the increased heating needs. In BRRR conditions in the 1984/85 heating season, the patterns are evenly spread over high wood use, moderate wood use, and low wood use patterns that are balanced by low electricity use, moderate electricity use, and high electricity use, respectively. So the most interesting variation in 1984/85 occurs in the BRRR conditions.

A somewhat similar pattern occurs for the 1985/86 heating season. Most MILD days fall into cluster 5, most COLD days fall into the moderate wood use/low electricity use pattern, and a wide variation occurs

Table 4.4 Cluster frequencies by outdoor temperatures(%)[a]

Row % Column% outdoor temperature	Cluster 1	2	3	4	5	Row Total N
1984/85 BRRR	22.7 30.4	21.3 66.7	29.3 64.7	17.3 65.0	9.3 6.9	75
COLD	46.8 64.3	9.1 29.2	15.6 35.3	7.8 30.0	20.8 15.8	77
MILD	3.6 5.4	1.2 4.2	0.0 0.0	1.2 5.0	94.0 77.2	83
Column Total N	56	24	34	20	101	235
1985/86 BRRR	28.7 40.4	27.4 64.5	2.72 40.0	1.9 53.3	19.2 12.7	73
COLD	39.5 57.7	14.5 35.5	4.01 60.0	8.4 46.7	23.7 16.4	76
MILD	1.3 1.9	0.0 0.0	0.0 0.0	0.0 0.0	98.7 70.9	79
Column Total N	52	31	5	30	110	228

[a]Reported are row percentages followed by column percentages.

among the BRRR days. A significant difference is that cluster 5 patterns are more prominent in the COLD days, indicating that retrofit allows households to use little wood and little electricity. Also, virtually no high electricity use days are reflected (cluster 3). Instead, wood use is increased in over fifty-five percent of the BRRR days.

These observations indicate that the change in patterns noted in the previous subsection are due mostly to changes in patterns exhibited by households for very cold days.

4.4 HOUSEHOLD CLUSTER ANALYSIS

The purpose of the exercise reported in this subsection is to explore whether groups of households choose sets of energy use patterns in a systematic fashion. If households do not, the data should indicate that each household utilizes each type of pattern (e.g., low electricity/high wood) the same percentage of the time. To conduct this analysis, records had to be constructed for each household that contained variables relating how many days the household chose each pattern listed in Table 4.1 and illustrated in Figures 4.4 to 4.5. Then the FASTCLUS procedure was applied to this data set using the five cluster variables preretrofit and the five cluster variables postretrofit as the clustering variables in each of two clustering runs.*

Table 4.5 presents the results. The results are good because there are satisfactory frequencies in each of the six clusters found in each analysis. Also, the clusters are easily interpreted by analyzing the types of days each cluster of households chose for wood and electricity space heating. For example, for cluster 2 in the 1984/85 heating season, one can surmise that these households primarily use wood and adopt a pattern of patterns that goes from low wood to moderate wood use as

*For example, for the 1984/85 heating season for each house in the sample, five variables were created, one variable represents the number of times the household utilized the cluster 1 (Fig 4.4) pattern for space heating, another variable represents the number of times this household utilized cluster 2, etc. These five variables were used to cluster houses according to their preference for space heating patterns.

Table 4.5 Household cluster analysis over pattern types

Household Cluster Number		F^b	Average number of pattern types by cluster[a] (Table 4.1) 1	2	3	4	5	Description[c]
1984/85	1	21	2.5	1.8	0.7	4.6	6.3	Outliers
	2	22	14.2	0.0	1.0	0.4	12.5	Low to moderate wood use
	3	8	20.0	0.5	1.9	1.0	4.6	Moderate wood use
	4	6	0.2	16.2	0.0	0.3	9.5	Low to high electricity use
	5	11	7.8	0.5	10.9	0.8	6.5	Low to moderate to high wood use
	6	24	2.6	1.4	0.1	1.3	22.2	Low wood and electricity use
1985/86	1	17	1.9	0.7	0.6	1.7	5.5	Outliers
	2	5	0.2	0.0	14.2	7.0	10.2	Low to high electricity use
	3	14	6.1	15.4	0.1	0.4	9.1	Low to high wood use
	4	15	2.0	0.7	0.0	1.1	26.3	Low wood and electricity use
	5	11	2.4	0.1	1.4	14.3	15.0	Low to moderate electricity use
	6	30	16.6	2.7	0.3	1.4	13.2	Low to moderate wood use

[a]For example, in the 1984/85 heating season, households that grouped together in cluster type 2, of which there are 22, 14.2 days of the 35 day season can be described by pattern 1 in Table 4.1 and 12.5 days can be described by pattern 5.

[b]Frequency

[c]Descriptions of the type "low to moderate wood use" indicates how those households change energy use patterns as outdoor temperatures drop.

temperatures move from mild to very cold. Additionally, cluster 6 households maintain low wood and low electricity use in all temperature situations.

Table 4.6 contains demographic descriptions of the household clusters. Three strong patterns are evident. First, households that move from low wood to high electricity use as temperatures drop have higher incomes and smaller family sizes (cluster 2 - 1984/85 and cluster 4 - 1985/86). Second, households that move from low to moderate to high wood use have larger families and had energy inefficient houses before retrofit (cluster 5 - 1984/85 and cluster 3 - 1985/86). Third, low wood/low electricity use houses are small in size (cluster 6 - 1984/85 and cluster 4 - 1985/86). Previous findings in this and the Tonn and White (1986) report are consistent with these findings. Somewhat surprising is the uniformity of how households with certain demographic characteristics chose similar wood use/electricity use patterns, at least among the 100 wood channel households.

Table 4.6 Demographic descriptions of household clusters

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Demographic Variable	Year											
	1984/85						1985/86					
	Outliers	Low to Moderate Wood Use	Moderate Wood Use	Low to High Electricity Use	Low to Moderate to High Wood Use	Low Wood and Electricity Use	Outliers	Low to High Electricity Use	Low to High Wood Use	Low Wood and Electricity Use	Low to Moderate Electricity Use	Low to Moderate Wood Use
Income ($)	29,800	25,700	26,000	40,000	35,500	20,400	36,000	31,900	25,700	27,400	21,700	25,600
Household members	3.52	3.18	3.13	2.67	4.18	3.17	2.40	3.35	4.42	3.50	3.00	3.03
Size house (sq ft)	1670	1360	1520	1530	1860	1330	1600	1700	1530	1380	1430	1470
Age head (yrs)	46	43	40	45	44	41	50	47	38	43	40	44
Age house (yrs)	24	20	24	32	30	17	41	18	27	27	22	18
Retrofit savings (kWh)[a]	8150	6560	9640	6370	9040	5030	8680	6920	8500	6730	6440	6630
Retrofit cost ($)[b]	5550	4390	7480	5850	5940	3700	6380	5400	5570	4600	4220	4800

[a] Estimated electricity savings for measures installed.

[b] Actual cost of measures installed.

5. ECONOMETRIC ANALYSIS OF WOOD USE

The task of this section is to econometrically analyze the submetered data to gain insights into the determinants of wood use. The strategy used is to first explore, through factor analysis, wooduser attitudes that were probed by the PNWRES (1984) survey. This analysis resulted in four factor variables that captured distinct outlooks on energy conservation. The factors are used in complex econometric models that, besides wood stove heat output, include electrical energy for space heating, other electricity use, and indoor temperature as dependent variables. Technically, the model is a lagged dependent variable, 3-stage least-squares (3SLS) system model that explores wood use through relationships to exogenous factors and endogenous variables.

5.1 ATTITUDE FACTOR ANALYSIS

As mentioned in Section 2, attitudes could significantly influence household behavior. As a result, every effort should be made to collect attitude data and incorporate attitude variables in the econometric models. The PNWRES survey contains a good set of attitude questions pertaining to indoor temperature comfort levels, preferences about thermostat settings when people are not home, and beliefs about energy efficiency. Table 5.1 lists eleven attitudes selected by factor analysis as most dominant in determining wood use.

To simplify data analysis, the eleven separate attitude variables were compressed into a smaller number of meaningful variables with factor analysis. It is reasonable to compress the eleven variables because households likely to answer one question a certain way would also be likely to answer another question in the same way. For example,

Table 5.1 Factor analysis of attitude variables (PNWRES84) wood channel homes only (N = 76).

Variable	Factors[a]			
	Non-conserver	Con-server	Pas-sive	Price-minded
1. Difficult to be comfortable when temp < 68°F	.58	-.08	-.15	.22
2. Reducing hot water temperature is worth doing	-.12	**.50**	**-.39**	.14
3. Reason to conserve energy is to save $	**.48**	.31	-.17	**.43**
4. When no one is home, turning down temp is worthwhile	-.04	**.55**	**.36**	-.08
5. It is hard to get around making home energy efficient	**.54**	.16	**-.39**	-.20
6. People have right to use as much energy as want	**.46**	-.10	**.50**	**-.39**
7. First price for appliances is more important than energy savings	**.38**	.33	**.36**	**-.42**
8. To conserve energy, must change lifestyle	**.57**	**-.41**	.10	.24
9. Home is efficient as can be	-.27	**-.39**	**.48**	.37
10. Energy scarcity is not a serious problem in state	**.44**	.27	**.40**	**.43**
11. Energy cost is not a serious problem in state	**-.38**	**.46**	.33	.27
Eigenvalues	1.98	1.39	1.38	1.08

[a]Entries are "loadings," or the correlations between each principal component/factor and an attitude variable.

households intent on energy conservation would probably find it easy to be comfortable when the indoor temperature dips below 68°F and would probably agree that reducing water temperature is worthwhile.

PROC FACTOR in SAS was used in the factor analysis. The results are presented in Table 5.1. Specifically, principal components analysis was used to find statistically significant groupings of responses, where the attitudes were assumed to be independent. Very generally, the principal components method analyzes the correlations among the responses to the attitude factors. For example, if one variable is highly correlated with another, then both would heavily contribute to the same factor. Two other variables that are highly correlated with each other but uncorrelated with the first two variables would heavily contribute to a second factor. Of course, correlations are never so orderly but this is the general approach.

The explanatory power of a principal component is measured by its eigenvalue.* By convention, components are considered strong if their eigenvalues exceed 1.0. In our analysis (Table 5.1), four factors stand out and have been interpreted as "nonconserver," "conserver," "passive," and "price-minded." For example, weighing heavily on the nonconserver component are the comfort and reason to conserve attitudes. With respect to the former, households that best fit the nonconserver profile find it hard to be comfortable at low indoor temperatures and only appreciate the economic benefits of saving energy. Other attitudes that weigh heavily on the nonconserver component include the perceived difficulty in making one's home efficient, the perception that energy

*See K. V. Mardia, J. T. Kent, and J. M. Bibby (1979) or D. F. Morrison (1976) for statistical treatment of common factor analysis.

conservation means lifestyle changes, and the perception that energy is not a problem anyway.

On the other hand, the conserver component has virtually the opposite weights. These households think reducing water temperature is worthwhile, that complete home efficiency has not yet been achieved, and that conservation should not require lifestyle changes. The passive households are not concerned about reducing water temperature but will turn down the thermostat when no one is home. To them, it doesn't seem difficult to retrofit houses and their houses are already quite efficient. They also believe that purchase prices for appliances are very important and that people should be able to use as much energy as they want. These seemingly contradictory weightings indicate that passive households are aware of conservation but have not really invested the time to understand the issues.

This is in contrast to the fourth component, labeled "price-minded." These households believe conservation saves money through deferred returns on wise investments in appliances. They also believe that energy is a problem and that everyone should be aware of it so that prices can be kept down. Conservation, though, is not without sacrifice because low temperatures are uncomfortable and conservation can adversely affect lifestyle.

Attempts to explain these four factors in terms of demographic profiles did not produce satisfactory results (Table 5.2). Regressions designed to reveal significant relationships* only produced a few

*Each of the four attitude factors were used as dependent variables in the regressions reported in Table 5.2. The dependent variables were constructed from the linear combination of the factor weights reported in Table 5.1.

Table 5.2 Four attitude factor regressions[a] (N = 76)

Independent variable[b]	Dependent variable			
	Nonconserver	Conserver	Passive	Priceminded
Intercept	3.31 (.00)	1.9 (.03)	5.65 (.00)	2.39 (.00)
INCOME84 ($)	-.00001 (.49)	.000006 (.59)	-	-
HHMEMB84	.18 (.23)	.18 (.16)	-.14 (.20)	-
HAGE84 (Yrs)	-.02 (.02)	-.0076 (.37)	.011 (.13)	.012 (.03)
RYEARS84 (Yrs)	-.05 (.06)	-.0098 (.62)	-.017 (.34)	.011 (.49)
AGE84 (Yrs)	-	.023 (.09)	-	-.016 (.06)
EDUC84 (Yrs)	.19 (.00)	-	-	-
BUDGET84 (Fraction) devoted to energy bills	-3.04 (.10)	-	-1.61 (.23)	-
ROOMS	.06 (.67)	-	(.27) (.27)	(.49) (.49)
HSYSAGE (Yrs)	.02 (.62)	-	-	-.015 (.44)
Adjusted R^2	.27***	.06	.08	.11*

*Significant at .10 level; ***Significant at .01 level.

[a]Coefficients above, probability > \|T\| in parenthesis below.

[b]See Fig. 5.1 for variable definitions.

findings and most of these are related to the nonconserver households. Somewhat counterintuitively, nonconserver households have higher educations, are more mobile, and live in newer houses. One could say, at great risk, that these households are up-scale, on the go, and too busy to bother with energy conservation. Conserver household heads are older and price-minded households live in older houses. Passive households are not demographically definable.

These regression results are not surprising, given that opinions and beliefs are formed in various ways under differing influences. Demographic influences need not color interpretation of facts or less certain information used to create the attitudes. Because these demographic data show such small influences, the attitude factors can be used in the 3SLS model with reduced concerns about multicolinearity.

5.2 3SLS SIMULTANEOUS EQUATION MODEL

The data sets available for this study are unique in the history of energy demand modeling. Most valuable are submetered data for wood, electricity, and indoor temperature. As an added feature, the electricity data can be broken into space heating and other end uses. As discussed in Section 1, data are also available pertaining to household demographic characteristics, housing characteristics, attitudes, audit and weatherization recommendations, and actions. Taken together, the data allow the estimation of econometric models that encompass a comprehensive range of household behaviors as determined by a wider range of independent variables. Specifically, for the first time, the data allow the specification of a model that encompasses, in a rigorous fashion, endogenous variables such as electricity use, wood use, and indoor temperature.

This modeling opportunity is important because it allows the study of wood use as part of the larger household energy environment. As seen in Sections 3 and 4, wood and electricity use for space heating are intertwined; one should be studied in relation to the other. If it is hypothesized that indoor temperature preferences directly affect demand for wood and electricity, then such preferences should also be included in a model. With the data at hand, such hypotheses can be explored.

Tonn and White (1986) offered a general discussion concerning approaches to modeling household wood consumption. They assumed that households make policy decisions about whether or not to use wood. These policy decisions then affect everyday decisions about when to use wood, how much to use, and who should collect the wood, etc. The model developed in this subsection can roughly be categorized as an everyday behavior model because all the wood channel households included in the analysis use wood.* The model does not quite describe everyday behavior because the dependent variables pertain to winter seasonal averages only. However, this compromise does not affect interpretation of the results.

The structure of the model and the application of the appropriate statistical estimation methodology are driven by the desire to model four household behaviors: (1) wood use for space heating in (kWh) equivalents, (2) electricity use for space heating (kWh), (3) electricity use for nonspace heating uses (kWh), and (4) indoor temperature (^{o}F).

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*This assumption is important because it eliminates the need to treat the wood kWh dependent variable as a truncated dependent variable, which would then require extremely sophisticated econometric techniques.

The first three dependent variables are summaries over a heating season, adjusted for missing values. For example, if one day's worth of wood kWh was missing for a household, then the total heating season value for wood kWh for that household would be adjusted upward by adding the kWh for an average day. The indoor temperature variable is modeled as the seasonal average, unadjusted for missing values.

Given the desire to use these four dependent variables, it is necessary to decide how to incorporate them (for the 1984/85 and 1985/86 heating seasons) into one model. Three options exist. One, a cross-sectional, time-series approach could be used. Two, models could be estimated with the differences in the dependent variables over time. Three, models could be estimated with lagged dependent variables. With the third option, the 1984/85 dependent variables would be treated as exogenous and specified in equations used to model the 1985/86 dependent variables.

The lagged dependent variable approach was chosen for theoretical and practical reasons. With respect to the former, the lagged variable controls for the inertia of past decisions, assuming that in general households exhibit only incremental changes in wood and electricity demands and in temperature preferences. Most simultaneous equation system models of the macroeconomy are developed using the lagged dependent variable approach. The cross-sectional, time-series approach also controls for past decisions but not enough years of time-series data are available to use this approach. The lagged dependent variable approach should be more than satisfactory to help reveal determinants of wood use.

The second major decision is the use of an estimation technique. Given four continuous dependent variables and the hypothesis that they are simultaneously determined, various simultaneous equation estimation techniques were examined. SAS offers two stage least squares (2SLS) and three stage least squares (3SLS). The latter was chosen because all four equations were over identified and data suggested significant co-variances between the error terms of the four equations (Theil 1971). With additional time, new econometric tests could explore more rigorously the appropriateness of the 3SLS approach.

The exogenous variables used to estimate the 3SLS, lagged dependent variable, four simultaneous equation system model are listed in Figure 5.1. Twenty-four exogenous variables and four lagged dependent variables are specified in different combinations in the four equations. Data are taken from the PNWRES survey, the project data set, and the submetered data sets. No 1986 survey data are used primarily because the sample size would have decreased significantly, from a maximum of 83 wood channel households with good monitored data that did not move in the past two years, to less than 50 households. Initially, all the endogenous variables were specified in all the equations. Insignificant endogenous and exogenous variables were dropped to increase R2s and to minimize the number of poorly specified variables. Approaches to specifying the exogenous variables varied. Some variables such as CENTRAL (heating) and WOODCOST naturally related to particular dependent variables, to AHEAT56 and AWOOD56, respectively, in these cases. Other variables such as HHMEMBER were difficult to specify in one equation *a priori*. These variables were typically entered in numerous equations and dropped when highly insignificant. Over 30 models were estimated, with the one depicted in Table 5.3 being judged as the best in terms of R^2s.

Fig. 5.1 List of variables used in econometric models

ENDOGENOUS VARIABLES
- AHEAT56 - kWh of electricity space heat - Oct. 1985 to March 1986 (HHD)
- AWOOD56 - kWh equivalent of wood space heat - Oct. 1985 to March 1986 (HHD)
- OTHER56 - kWh of electricity for nonspace heating - Oct. 1985 - March 1986 (HHD)
- WINTMP56 - Monitored indoor air temperature - average daily - Oct. 1985 to March 1986

LAGGED ENDOGENOUS VARIABLES
- AHEAT45 - kWh of electricity space heat Oct. 1984 - March 1985
- AWOOD45 - kWh equivalent of wood space heat Oct. 1984 - March 1985
- OTHER45 - kWh of electricity for nonspace heating Oct. 1984 - March 1985
- WINTMP45 - Monitored indoor air temperature - average daily-Oct. 1984 - March 1985

EXOGENOUS VARIABLES
- AREA1 - =1 for PP&L customers, =0 for HREC customers
- BUDGET84 - % of household budget going to electricity bills (PNWRES84)
- CENTRAL - =1 for households that have central heating capability =0; otherwise (PRWRES84)
- NONCONSERVER - Constructed from attitude variables - higher value indicates no conservation (PNWRES84)
- EDUC84 - Education level of household head (yrs) (PNWRES84)
- EFFIC - Estimated retrofit savings/recommended retrofit savings (pro ject data)
- FDAY - Reported average, day-time thermostat setting (PNWRES84)
- FEVE - Reported average, evening thermostat setting (PNWRES84)
- FNIT - Reported average, night-time thermostat setting (PNWRES84)
- AGE84 - Age of house (PNWRES84)
- HMEMB84 - Number of household members (PNWRES84)
- IMPROVE - Effic/(aheat45 + awood45)
- INCOME84 - Household income (PNWRES84)
- CONSERVER - Constructed from attitude variables - higher values indi- cate supportive energy conservation (PNWRES84)
- OWN84 - =1 if home is owner-occupied; = 0 otherwise (PNWRES84)
- OTHERUSE - Sum of dummy variables related to possessing electric durables; range [0-15] (PNWRES84)
- PASSIVE - Constructed from attitude variables - higher value indicates more understanding of conservation and easy things done (PNWRES84)
- RYEARS84 - Number of years in present residence (PNWRES84)
- SINGLE - =1 if single family detached; = 0 otherwise
- SQFT - size of home (project data)
- STOVE - =1 if home has wood stove; = 0 otherwise (PNWRES84)
- THERMO - =1 if home has manual thermostat; = 0 otherwise (PNRWES84)
- TODDLER - =1 if household has individual between 0 and 5 years old (PNWRES84)
- WOODCOST - =1 if wood cost is a problem; = 0 otherwise (PNWRES84)
- ROOMS - Number of rooms in the house (PNWRES84)
- HSYSAGE - Age in years of the primary heating system (PNWRES84)

Table 5.3 3SLS model (beta coefficients) (N = 76)[a]

DEPENDENT VARIABLE	AHEAT56	OTHER56	WINTEMP56	AWOOD56
(N=76) (R^2)[b]	(.89)	(.89)	(.79)	(.82)
AHEAT56	X	.05 (.16)	-	-
AWOOD56	.89 (.14)	-	-.00016 (.15)	X
OTHER56	-	X	-.00009 (.42)	-
WINTMP56	-153 (.00)	-	X	-13 (.80)
AHEAT45	.67 (.00)	-	-	-
AWOOD45	-	-	-	.59 (.00)
OTHER45	-	.71 (.00)	-	-
WINTMP45	-	-	.76 (.00)	-
INTERCEPT	9763 (.01)	-1387 (.04)	6.0 (.33)	1630 (.70)
AREA1	-	-	-1.14 (.03)	-
BUDGET84	-	3016 (.00)	-	-
CENTRAL	1069 (.00)	-	-	-
NONCONSERVER	122 (.14)	-	-	-
EDUC84	-	-	-	-
EFFIC	-1240 (.00)	-	-	-
FDAY	71.5 (.00)	-	-	-
FEVE	-	-	.099 (.10)	-
FNIT	-	-	.08 (.04)	-
HAGE84	-	8.66 (.14)	-	-
HHMEMBER84	-	231 (.02)	-	-
IMPROVE	-	1,714,194 (.03)	1636 (.39)	-

Table 5.3 3SLS model (beta coefficients)(N = 76)[a] (Cont.)

DEPENDENT VARIABLE	AHEAT56	OTHER56	WINTEMP56	AWOOD56
INCOME84	-	.013	-	-1026
		(.12)		(.05)
CONSERVER	-	-	-.15	-
			(.38)	
OWN84	-2780	765	-	-
	(.00)	(.17)	-	-
OTHERUSE	-	151	-	-
		(.08)		
PASSIVE	-100	-	-	-179
	(.41)			(.17)
RYEAR84	-	-	.072	36.2
			(.01)	(.09)
SINGLE	-	-	-.85	-807
			(.23)	(.11)
SQFT	-	-	-	.91
			(.04)	(.04)
STOVE	-	-	1.45	563
			(.12)	(.37)
THERMO	-	-	.78	-
				(.11)
TODDLER	681	-	-	-670
	(.12)			(.16)
WOODCOST	-	-	-	609
				(.10)

[a]Significance levels are in parentheses.

[b]R^2 for the entire model is 0.88.

Observations on the results are broken into discussions about the performance of the endogenous and exogenous variables. With respect to endogenous variables, the results are mixed. On the positive side, the lagged dependent variables are highly significant. In fact, they dominate the models and are the main reasons for the extremely high R^2s (from .79 to .89). In runs without the lagged variables, no R^2s exceeded 0.45 and two were in the range of 0.20. These types of results are typical for lagged dependent variable models.

The simultaneously defined endogenous specifications (e.g., WOOD56, AHEAT56) proved disappointing. Only six of twelve possible specifications remained in the best model, and of those six, only one is highly significant. Three may be considered as borderline significant and two are quite insignificant. Basically, the results indicate that nonspace heating electricity decisions are independent of the other three types of decisions because none of the other decisions affect them. Electricity space heating decisions appear to precede indoor temperature decisions in a negative fashion and wood use in a positive fashion, a relationship found in previous work. Temperature decisions in turn negatively affect wood use decisions.

Numerous interpretations could be deduced from these results. The one we favor is the following. Once the decision to use wood has been made, then everyday decisions focus on how much electricity to use. The more electricity a household needs to consume for space heating, the greater incentives there are to conserve or decrease electricity consumption. Thus as electricity needs increase, households will reduce indoor temperatures and displace electricity with wood. The fact that wood use does not interact significantly with any of the endogenous variables supports this interpretation. What this interpretation means is factors related to electricity use should affect the electricity/wood ratios more than factors that relate to wood use.

One characteristic of large simultaneous equation models is that the interpretations of the exogenous variables are virtually endless. Intricate explanations of why certain variables were or were not significant and in what combinations are possible. The remaining discussions in this subsection address the exogenous variables and highlight what are considered to be the most important observations. The reader should not be deterred, however, from exploring additional interpretive avenues.

Interesting observations are derivable from the economic, demographic, dwelling, and attitude variables. The economic variables generally perform as expected. For example, among woodusers, income is negatively related to wood use, which is a familiar result for households that have already chosen to use wood, and positively related to nonspace heating electricity use. Having central heat, which is a relatively convenient and high quality electric space heating system, is positively related to space heating consumption. The EFFIC variable, which is calculated from the project data to represent postretrofit house efficiency is, as expected, negatively related to electricity space heating consumption. IMPROVE, another variable developed from the project data, is significant in the indoor temperature equation. This result indicates some take-back (i.e., households increasing indoor temperatures postretrofit).

One shortcoming of the model is the lack of variation in price data. AREA1 is a dummy variable indicating whether the household resides in the PP&L service area or the Hood River Co-op area. Electricity prices in the PP&L area changed between the two heating seasons but did not change in the Co-op area. Thus the dummy variable was sufficient to represent relative prices. Equipment costs were not available and wood costs were difficult to determine with any reliability. This is because only 20% of the households purchased any wood, and no commercial wood vendors for residential space heating could be located in the Hood River area to provide prices.

Given the difficulties with price data, we were appreciative of the fact that the AREA1 variable behaved as expected. Although it wasn't significant in either the wood or electricity equations, it is highly significant and negatively related to indoor temperature readings. In effect, higher prices in the PP&L service area translated into lower indoor temperatures.

Two results related to demographic variables are worth mentioning. One, the presence of toddlers is negatively related to wood use, presumably because the hot equipment presents real dangers to small children and taking care of children created a lack of time for the extra work of using wood. This variable is also positively related to electricity space heat consumption, possibly because more people are home during the day. Two, larger households are associated with the use of more electricity. Disappointingly, two classical demographic variables, education and age of the household head dropped out of all the equations.

Variables associated with housing characteristics performed in ways to make convincing interpretations difficult. Most straightforward is the observation that larger homes use more wood. Another observation is that single family homes have lower indoor temperatures, which might make sense if numerous multifamily dwelling units do not have individual thermostats or if households living in such units have preferences for higher indoor temperatures. On the other hand, owner-occupied units use less electricity for space heat, which might make sense if most renters do not directly pay electric bills, but this is not the case in this study.

The attitude variables performed, if not highly significantly, then at least in interpretable ways. NONCONSERVER households use more electricity than CONSERVER households and have higher indoor temperatures. PASSIVE households use less wood and electricity for space heat than the other types. Each of these findings fits well with the interpretations of the factors in the previous subsection.

In conclusion, the 3SLS model offers many useful insights concerning the relationships between the endogenous variables and their determinants. With respect to wood use, electricity and indoor temperature decisions appear to precede wood use decisions. Income and house size are significant determinants. As caveats to this analysis, it should be mentioned that from an econometric point of view, much more could be done with this approach. Tests could be conducted to justify the use of 3SLS, and software not available in SAS might be required to estimate new models. Also, we saw that model coefficients were very sensitive to the exact specifications of the exogenous and lagged dependent variables. Numerous model runs were made but no assurances exist that the model presented in Table 5.3 is optimal. The model is, however, highly significant and quite satisfactory from a common sense view and an econometric perspective.

6. SUMMARY AND DISCUSSION

This last section of the main body of this report presents a summary of findings and their policy implications and recommendations concerning future work.

6.1 SUMMARY OF FINDINGS

The four analytical sections contain numerous interesting and important findings. Before summarizing specific findings, a few general comments are in order. First, for the 100 wood channel households, wood use for space heating is very important and its importance did not diminish after retrofit. Second, extending findings made specifically about the 100 homes or about the entire monitored home sample (N=320) to other areas in the Pacific Northwest is defensible; HRCP woodusers resemble regional woodusers across many characteristics important to wood use (see Table 2.2).

In Section 2, wooduser profiles were developed. The typical wooduser owns a larger and older home and has a large family. Use of wood increased slightly from 1983/84 to the preretrofit year (1984/85) but then, as might be expected, declined thereafter (in 1985/86). Unfortunately, reports of wood use in terms of cords consumed per heating season appear fairly unreliable. Woodusers use wood because of economic factors: wood is less expensive and fuel costs need to be cut. Wood is not used for aesthetic reasons, although it is often judged to be more comfortable than electricity. Finally, lower quality woods are used for most wood heating needs; higher quality woods are used for supplemental heating.

Wood displaced a great deal of electricity for space heating in the 100 wood channel homes (Section 3). Indeed, space heating energy provided by wood stoves is 1.7 to 4.5 times greater than electrical space heating energy in those same homes. Woodusers also use more total energy for space heating than nonwoodusing homes, about 20% more. Correspondingly, wood using homes saved 3.1 to 12.5 times more total energy in space energy than nonwoodusing homes after retrofit. In terms of saving energy (i.e., electricity and wood combined) for space heating, HRCP investments in woodusing homes were much more cost efficient than investments in nonwoodusing homes. In terms of saving electricity, the most effective investments were in nonwoodusing homes. This last finding is of particular interest to conservation program planners.

Households basically fall into five daily wood/electricity patterns. The patterns represent a mixture of wood and electricity use intensity levels. The nature of the patterns did not change appreciably from pre- to postretrofit, although the postretrofit patterns represent lower overall energy consumptions. However, households showed fewer high electricity use patterns in 1985/86 and tend to favor high and moderate wood use patterns that were linked with low and moderate electricity use patterns, respectively. Surprisingly, the choice of energy use patterns did not relate to day of the week considerations. Instead, outdoor temperature appeared to drive pattern choices. For mild days, most households used low wood/low electricity patterns. For cold days, moderate wood use patterns were chosen. For very cold days, the variation in pattern choices increased appreciably.

The data sets available to this study offered unique opportunities for econometric analysis. A 3SLS, lagged dependent variable, four equation simultaneous equation system model was estimated with wood kWh equivalent, electricity for space heating kWh, other electricity kWh, and indoor temperature as dependent variables. Endogenous interactions between the four dependent variables suggest that electricity decisions precede indoor temperature and wood use decisions in households that already have chosen to use wood for space heating. The lagged dependent variables played a major part in yielding high R^2s for the four equations. To summarize a few interesting independent variable results, among woodusers, central heat is positively related to electricity space heat use, income is negatively related to wood use, efficiency changes in the home due to retrofit are negatively related to electricity space heat use, the presence of toddlers is negatively related to wood use, and a "conserver" attitude profile is related to lower indoor temperatures.

6.2 POLICY IMPLICATIONS

A major purpose of the study is to provide useful information for power demand and supply analysis in the Pacific Northwest. The following discussion represents a few ways the results reported herein may be used to contribute to such analyses.

The results reported in Section 3 clearly indicate that wood is a major fuel in the Pacific Northwest. The easiest way to track residential wood use is to regularly survey households on how much wood they use. Unfortunately, results in Section 2 indicate that household reports of cords consumed do not correlate well with heat actually output into houses from wood burning equipment. The implication is that more than minimal effort is needed to confidently track wood use.

Because wood displaces so much electricity in woodusing homes, a good market for electricity is those homes. The profiles provided in Section 2 should assist in identifying woodusing homes. The pattern results presented in Section 4 could help in developing marketing strategies. For example, a utility could offer electricity price discounts on very cold days or during times of peak wood use (e.g., early evening).

A concern that Bonneville should have is that the wood use market is not saturated. The small number of heavy woodusing houses use much more wood energy than the average wood using houses, and a large number of homes still do not use wood. Thus, future increases in electricity prices could result in more electricity being displaced by wood. More information on why some houses do not use wood would assist in defining an upper limit to residential wood use in the Pacific Northwest.

The econometric model results suggest that the above implication of electricity price increases should be studied seriously. This is because the model indicates that electricity use decisions precede wood use decisions. Thus, a change in electricity prices could affect electricity, and consequently, wood demand in volatile manners.* Therefore, electricity pricing policies must be sensitive to large price elasticities.

Fortunately for Bonneville, it appears that residential weatherization reduces the potential volatility in electricity demand (App. B).

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*This point is better seen if we had found that wood use decisions precede electricity decisions. Assume that not much changes about wood because households cut their own (i.e., no price change) of the same type of wood year in and year out. Because nothing would change to push households from using wood, large changes in electricity prices would have to occur to result in marginal changes to wood demand.

Even by weatherizing heavy woodusing homes, Bonneville gains by reducing that home's potential electricity demand. Bonneville could save money, therefore, by reducing peak load capacities and deferring plans to acquire new power supply resources. More analysis is required to quantify these benefits of conservation.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

This subsection focuses on two topics, data and data analysis. Data could have been improved in four ways. First, the entire sample of 320 submetered homes should have completed the Wood Heating Survey. These homes represent an enormous resource and the submetered data have been gathered at a significant cost. Under these conditions, every effort should have been made to make the submetered data as useful as possible. Having a completed Wood Heating Survey for each of these households would have enabled more rigorous econometric analysis. In future wood surveys, nonwoodusers should answer all attitude questions. In the survey used herein, the nonwoodusers were instructed, needlessly we believe, to skip questions pertaining to attitudes toward wood use. The analysis would have been strengthened if input from nonwoodusers had been included.

Overall, the socioeconomic data available for the study are of high quality. Almost all variables, important for analysis, can be found in at least one of the various data sets. Unfortunately, most of the demographic variables lack a time element. That is, the data are gathered for only one point in time whereas the energy consumption data extend over a number of years. Changes in energy consumption, for either electricity or wood, may be due to changes in the efficiency of the house and/or may be due to changes in income, household size, or even house size. Attitudes may even change in a short period of time. Thus, at the cost of being increasingly intrusive, it would be worthwhile to consider collecting even more data from the sample households when multiple years of energy consumption data will be available.

An important area for improvement is that of prices. First, a method is needed to establish wood prices. Hansen (1977) presents a method to calculate the cost of cutting your own wood, which includes sawing costs, labor, and transportation. If such a method is to be used, data must be collected for all households to allow the calculation. Also needed are means to better determine the cost of purchased wood. Even though few if any commercial dealers exist, random surveys of local wood peddlers and checking newspaper ads would at least provide some information. Second, more variation in electricity prices would have been valuable. Submetered houses in ten different service areas with ten different price schedules would allow a superior examination of the effect of electricity prices on the complex interaction of electricity consumption, wood consumption, and indoor temperature settings. Third, data on price expectations and the price of various equipment options would also have been useful.

Last, it would have been interesting and more enlightening to have comparison questions about attitudes. Is wood less convenient than electricity? If you had an extra $10,000 in income would you heat with more electricity, wood, or keep consumption the same? Is wood preferable to natural gas? If wood became slightly harder to obtain, how much would you decrease your wood use? Answers to questions like these, and utilization of wood use models, would be very valuable in helping to reliably predict wood use in the future.

Even without improving data resources, additional work could focus on improving data analysis. As mentioned in Section 5, the 3SLS model, while extremely satisfactory, may not be the optimal econometric model. New tests are becoming available to assist analysts in determining the suitability of the numerous estimators of simultaneous equation systems. In addition, some sensitivity in model results was observed due to changes in model specification. If Bonneville desires to use the 3SLS model for predictive purposes or for highly sophisticated analyses, then it may be wise to invest more resources in model development.

Additional econometric analysis could focus on how households choose daily patterns. Do households choose a set of patterns? Or do households choose patterns based on weather forecasts and daily time schedule? A very interesting (and ambitious) study could attempt to merge 15-minute data with 15-minute diaries of activities carried out by household members. Such a study would reveal responsibilities for wood burning operations and directly link energy consumption to everyday behavior.

To extend this discussion from mere speculation to serious planning, Bonneville could consider new analytical techniques being developed in artificial intelligence (AI). Much relevant work is being done in the machine learning area. Data driven machine learning algorithms are given examples of data patterns and are expected to uncover knowledge that explains the patterns. For example, an algorithm could be given medical cases and diagnoses. The algorithm would determine the rules that the physicians use to make their diagnoses.

Machine learning could be related to this research in the following way. An algorithm is given 15-minute patterns over a day for each of the important channels (i.e., electricity, wood, and indoor temperature). These patterns are treated as diagnoses. Symptoms would be day of week, season, and outdoor temperatures. The algorithm would find the rules a household uses to choose a daily energy consumption pattern. A set of rules for each household could then be used to simulate each household's behavior. Instead of having statistically-based mathematical models that yield predictions on the behavior of an average house, Bonneville would have computer databases or idealized reproductions of actual household decision making behavior.

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APPENDIX A.

DATA QUALITY

While some researchers might refer to the HRCP as an "evaluator's dream," other researchers might refer to the HRCP as an "evaluator's career challenge." Data processing and management needs would appear to increase exponentially with the number of data sources that contain data on a primary unit of analysis across similar variables over time. In other words, data sources could be seen as competitors in providing precise and accurate information about, for example, a survey respondent's self report of attained educational level, as recorded on two surveys, administered 30 months apart. Furthermore, HRCP's unique data--submetered total electricity, electricity for space heat, and electricity for water heating/wood space heating use, and indoor temperatures at 15-minute intervals for each one of 320 houses, for 730 days*--require extraordinary attention in processing and management, particularly in the initial stages of measurement, collection, and recording. The unit of measurement for the submetered data is a unit that is common to nearly all residential energy consumers; consumption is measured in kWh and temperature is measured in ^{o}F. However, the reporting of wood heating use in units of kWh (based upon measures of radiant heat transfer of stoves) is not common and, in truth, might be considered an extreme departure from the norms of hard science.

Our purpose in this appendix is to explain the data processing methods involved with collecting the submetered data, particularly as

*If each 15-minute interval and each channel is represented by a unique data record for each house, then the submetered data alone generate 99,702,400 observations.

they regard the wood space heating channel, and to compare selected competing information from various data sources. It should become clear there is only a slight distinction between "dream" and "challenge."

SUBMETERED DATA COLLECTION

Most residential energy users are familiar with the typical electric meter that records the number of kilowatt hours (kWh) used during a given billing cycle. The submeter devices installed in the monitored houses to measure total electric, electric space heat, and water heating use are quite similar to the typical electric meter. The basic difference is the presence of a pulse initiator in the submeter device. The pulse initiator sends three rapid electronic signals to a recorder when the dial on the submeter completes five (5) revolutions. The recorder sums these pulses for each 15-minute interval and then stores the number of pulses accumulated during the intervals. These measurements are accurate within ±3%. Once each month, an HRCP project technician visits each monitored house site, and collects the pulse records. Data technicians apply the appropriate scaling factors to convert pulse counts to load and energy units. In particular, load is calculated by multiplying the number of pulses per interval times the scale factor [kWh/pulse] times 4 [interval/hour] and consumption is determined by multiplying the accumulated pulses for any time period of interest times the scale factor.

The processing of the wood heating channel data deserves more detailed explanation. In this report, the wood stove energy output is reported in kWh units. However, translating radiant heat from wood stoves into equivalent electric energy units involves a considerable amount of time and effort. In the HRCP, extensive efforts were undertaken to measure and translate the radiant heat output of the 100 houses equipped with wood heating submeters.

The primary objectives of these efforts were two-fold: (1) to measure the contribution of woodfuel to the total space heating needs of the household, and (2) to measure this contribution of woodfuel in a way that permits comparison to electricity in similar energy units.

Modera, Wagner, and Shelton (1984) tested five wood stoves typical of those found in the Hood River area. Twenty of the 55 wood heat monitored households which completed the 1986 Wood Heating Survey reported they had stoves which are similar if not identical to the stoves tested. The purpose in testing the wood stoves was to find a single-channel sensor whose output could be correlated with the heat output of a wood stove (measured by 32 sensors in a calorimeter room).

The wood stoves were monitored with thermocouples and radiometers during operation in a calorimeter room. Several physical models (i.e., radiative, natural convection, and linear) were used to describe the heat transfer from the stove. All tests were performed with three radiometers in place, each aimed at different stove surfaces. These data were used to determine an optimal location and the variation among locations.

Since radiometers measure a representative sample of the radiative flux leaving the stove, the researchers hypothesized that the radiometers should correlate with the heat output of the stove as measured in the calorimeter room. A correlation parameter was estimated based upon the ratio of the average heat output to the average sensor (radiometer) reading for the physical models indicated above. The researchers found that "radiometers provide accurate results using a single correlation parameter for all stoves" tested. Furthermore, the researchers indicated that individual or stove-specific correlation parameters can be much more accurate.

The researchers list of recommendations for the HRCP field applications, besides radiometers in lieu of thermocouples, included the recommendation that the radiometer be placed at the left rear of the stove and aimed, also, at the left rear. However, structural and other constraints during installations required radiometers to be placed in locations different from those tested in the calorimeter room. Based upon recommendations from Modera (1986) and PP&L technicians, PP&L HRCP staff revisited households that had wood heating channels to collect additional data that would support, and to some extent enhance, the transfer of the wood stove tests from the laboratory to the field. In this second stage of research, Modera (1986) used the existing empirical data recorded in the laboratory and view-factor analysis to determine individual, site-specific correlations for the actual radiometer locations. The site-specific correlations accounted for the angles between the radiometer and various stove surfaces, the distance from the radiometer to the stove, stove pipes blocking the sensor's view of the stove, and convective heat transfer. Modifications were necessary, however, to develop individual correlation parameters for fireplace inserts, radiometers located beside stoves, and stovepipes located at the back (rather than at the top) of the stove. Correlations predicted with the view-factor model in the second stage are similar to correlations developed in the laboratory, within 9% on average with a standard deviation of 8% (Modera, 1986).

Since radiometers convert radiant heat to voltage measurements, the second of the two primary objectives can be attained with a rather straightforward computation. The radiometers were equipped with integrators, devices that use volts as inputs, convert the volts to pulses, and send electronic signals to a recorder for storage. (All submeters were similar at this point of data collection and management). The integrator sends 3000 pulses to the recorder for every 250 watts/M^2 of radiant heat measured by the radiometer. Watt-hours (wh) for every 15-minute interval can then be computed as follows: $wh = \Sigma$ pulses *.083 *c.p., where .083 (i.e., 1/12) is a constant across all households (and standard in this conversion process), and c.p. is the site-specific correlation parameter for each wood stove. The wh value then would have no more error than the correlation parameter itself. Furthermore, the wh values would vary about the mean of wh just like the c.p.s vary about the average c.p.

In other words, although we do not know the precise error involved with the radiant heat-radiometer-wh measurement process for each wood stove (only for those tested), we can expect the distribution of these errors to counter one another, much like standardized values counter one another in a normal distribution. At least for the application of the wood heating channel in this study, we are comfortable with the accuracy and precision of our group comparison analyses, where, for instance, we compare mean values of wood space heating for woodusers with mean values of electric space heating for nonwoodusers. Similarly, we feel that the summing of group mean values of wood space heating with electric space heating is defensible. We do not, however, support comparisons of one house versus another house whenever the compared variable is the wood heating channel.

COMPETING DATA SOURCES

Table A.1 lists the data sources from which all variables used in this study were derived. The time at which the data were collected and the kinds of information solicited or observed are also indicated, in addition to the method used to collect the data.

Electric utility bills, audit and retrofit data related to the auditor's assessment of the thermal integrity of the house, and end use load data have only one data source. However, household and housing data are available from two and, frequently, three data sources.

Table A.1. Data sources for the wood heating study of the HRCP

Data source	Method of collection	Time collected	Data classification
Electric utility bills	Historical	1986	Electricity consumption records
Audit	Varied	1983-1985	Heat loss estimates, household and housing characteristics
Load	Direct	1983-present	End-use consumption data and interior temperature
PNWRES survey	On-site	1984	Household and housing characteristics
1986 Wood Heating Survey	Mail	1986	Household and housing characteristics

The household and housing characteristics were extremely important to this study in many ways, particulary in the classification and description of woodusers, heavy woodusers, and nonwoodusers. Early in our study, we elected to utilize the PNWRES survey as the principal data source for household and housing characteristics for very practical reasons. First, we were familiar with the survey instrument and the inclination of certain questions to elicit certain responses. In other words, we were comfortable with the assumption that respondents answered questions based upon a clear understanding of the question. (This is a presumed advantage of the presence of a skilled interviewer). Second, the PNWRES survey was administered before the house entered even the preretrofit year (1984/85). Consequently, survey influences on energy consumption could be minimized in the postretrofit year (1985/86). In other words, the survey would not "encourage" extraordinary program savings as promoted through the enhanced awareness of householders to conserve. Third, householders were surveyed at nearly the same time. In short, the influences on energy consumption not measured could be seen to influence the householders simultaneously if not identically. These influences might include the marketing of HRCP through video and print ads and "talk-of-the-town" due to the high profile of HRCP. Fourth, since we were primarily concerned with wood space heating at the start of project operations, we needed to classify and describe wood use before the houses were treated. It was critical to define them before the program influenced their wood using behavior.

Nonetheless, we used other data sources for measuring household and housing characteristics when our study so indicated the need (e.g., when measuring change or substituting for missing values from the PNWRES survey). It then became important to assess the consistency of competing data sources.

Table A.2 shows the overall mean values by data source for the variables most important to our study that appeared in more than one data source. Given the differences in time collected across data sources, the consistency of competing data sources is fairly well assured. When adjustments are made to the variables that change values due to time alone (age of house, length in residence) there are no statistically significant differences between data source means. We believe that the

Table A.2. Consistency in the mean values of variables from competing data sources[a,b]

Variable (N)	Data source: PNWRES/ Audit (246)	Audit/ 1986 (162)	PNWRES/ 1986 (162)
Age of house (years)	21.0/21.9	-	-
Percent who own[c]	92.3/94.7	96.3/92.6	95.1/92.6
Length in residence (yrs)	9.9/10.7	11.7/12.8	10.2/12.5
Household size (persons)[c]	2.9/3.0	2.9/2.8	2.8/2.8
Household income (1982 $)[c]	27,818/27,438	-	-

[a]Means are based upon matched, nonmissing values for variables indicated.

[b]Data source to right or left of "/" corresponds with mean values to right or left of "/".

[c]Differences could be related to real change in the variable measured rather than the different times at which the data were collected. In other words, homeowners buy and sell houses, people move in and out and add permanent new faces, people get raises or lose income.

differences that do exist are primarily the result of respondent/ interviewer error or data source design. We conclude, then, the present study does not suffer from the competition among data sources. In fact, the data sources, despite their methodological or design differences, probably contribute to a more complete study of wood use.

APPENDIX B

PREDICTING CHANGES IN RESIDENTIAL ELECTRICITY USE DUE TO WEATHERIZATION

Change in energy consumption is a major and continuing concern for U.S. utilities, particularly in periods of fuel price instability. Additional complications arise when conservation savings are treated along with generating/distributing facilities as energy resources in system planning and energy demand and supply forecasting. When only one fuel is used for space heating among households in a utility's service area, measuring changes in energy consumption would seem less problematic than measuring changes where households use fuels in combination, especially electricity with wood, to meet their space heating needs. In the Pacific Northwest, fully 48% of the households have the potential to burn wood exclusively for space heating (Tonn and White, 1986, Table 4.6). Among the submetered houses analyzed in this report, 74% use wood for some or all of their space heating.

In this appendix, we estimate the range of uncertainty involved in the prediction of energy savings expected as the result of participation in the Hood River Conservation Program (HRCP). We provide estimates of this range of uncertainty based upon changes in consumption and, alternatively, changes in average demand. We focus on the residential energy use patterns where (1) electricity is the exclusive space heating fuel and (2) wood is heavily used and there is little if any electricity used for space heating. The difference in electricity use between these extreme cases is the range of uncertainty (of electricity consumption and, alternatively, of energy demand), relative to the actual energy savings achieved by all residential energy using customers.

We used data from the 1984 survey and the 1986 Wood Heating Survey to estimate savings for electricity only and heavy wood use households.* We define heavy wooduser as a wooduser that ranks above the median value of the variable. The value of the ranking variable for each wooduser is based upon the wooduser's intensity in using wood for space heating. For example, we assigned a larger value to a reported cords use of 8 than to a reported cords use of 2, under the assumption that 8 cords contribute more to space heating. In addition to the self report of cords used, we also ranked woodusers based upon their self reports of using wood as a primary or supplemental space heating source. See pages 13 and 14 for additional information on definitions of wooduser and heavy wooduser.

After selecting the electricity only and the heavy wood use households, we estimated separate energy savings regression models for these households. We retained variables with coefficients that were significant at the .10 level; next, we computed predicted savings, post hoc, for all households by multiplying observed values by the significant coefficients. The results of this process are shown in Table B.1.

As indicated in Table B.1, electricity only households overestimate the savings of all households; heavy wood use households underestimate savings.

This is the opposite to findings in Tonn and White (1986) where all-electric customers underestimated and heavy woodusers overestimated

*N=184, the intersection of households with 1984 surveys and households with 1986 surveys.

Table B.1. The range of uncertainty in predicting the change in residential electric energy use after weatherization due to all-electric (no wood) use and heavy wood use conditions[a]

	Electricity		Wood	
	Electricity only[b] (46)	All houses (184)	All houses (184)	Heavy woodusers[b] (69)
Preretrofit NAC	18650	19230	19230	17060
Actual electricity savings	2270	1780	1780	900
Predicted electricity savings[c]		2180	830	
Uncertainty (%)[d]		-22.5	53.4	
Range (%)		75.8[e]		

[a]Estimated over participants only, expressed as kWh/year.

[b]Wooduser is defined on p. 13; heavy wooduser is defined on p. 14; electricity only customers are those customers that are <u>not</u> woodusers.

[c]Regression:

Actual savings (DNAC) for houses = $b_o + b_1X_1$ (1) $+ \ldots b_kX_k$, where $X_1 \ldots X_k$ are observed values and $b_o \ldots b_k$ are parameter estimates of the model, and where X =[(PRENAC, audit estimate of retrofit savings for measures installed, age of the household head, electricity billed on a budget basis (0,1), home ownership (0,1), change in winter indoor temperature) for electricity only customers] and [(PRENAC, house size (square feet), audit estimate of retrofit savings for measures installed, household size (persons), customer estimate of wood used for space heating (%), customer report of change in amount of wood burned (cords)) for heavy woodusers].

Computation:

Predicted savings (PSAV) for all houses = Intercept, + (2) $\text{Coefficient}_1 * X_1 + \ldots \text{coefficient}_k * X_k$, where $X_1 \ldots X_k$ are observed values of the significant parameter estimates of (1) and Intercept, $\text{Coefficient}_1 \ldots \text{Coefficient}_k$ are parameter estimates of (1) used as constants in (2).

[d]Uncertainty (for all houses) =
[(actual savings - predicted savings)/ actual savings] *100%. (3)

[e]$[(PSAV_{electricity} - PSAV_{wood})/DNAC_{all\ houses}] * 100\%$,
or the sum of the absolute values of the two uncertainties. (4)

program savings. Part of this reversal might be due to our more liberal definition of heavy wooduser here and to the maximized participation of woodusers in the HRCP. In Tonn and White (1986), a heavy wooduser was a wooduser that ranked in the top 10% of a ranking variable developed like the one used in the present study. Since woodusers, and heavy woodusers, did not participate in the three programs* examined previously at the same or similar rate as in HRCP, then we possibly selected a small and nonrepresentative fraction of woodusers and heavy woodusers in our previous study. In this study, however, woodusers participated at the rate of 100%, given the financial incentive of HRCP that removes the common barrier to woodusers participating in retrofit programs.

As we reported in our original study, we suggested that woodusers burn wood for space heating in lieu of participation in conservation programs. We believe that the relationships between electricity-only, heavy-wood-use, and all-household actual savings and predicted savings in Table B.1 are the logical relationships for two reasons.

First, wood use displaces electricity use. That is, virtual conservation of electricity exists where wood fuel burning, or any other fuel, takes the place of electricity for space heating. Virtual conservation, then, is the amount of electricity not being saved because some other fuel is being used. Second, heavy woodusers can reduce both electric and wood space heating as the result of the direct benefits of a conservation program like HRCP. As a consequence of retrofit programs, electricity use cannot decline as much in wood burning households because electricity is not the exclusive space heating fuel.

*BPA Pilot Residential Weatherization Program, and the 1982 and 1983 editions of the BPA Interim Residential Weatherization Program.

Nonetheless, electricity is being saved--virtually--since the demand for energy involves the burning of wood to displace electricity, but not at the rate that electricity-only households save.

The alternative view to changes in consumption illustrates the potential error (uncertainty) in projecting residential sector electricity demand on the premise that no wood is being used for space heating in the BPA region. In other words, we are concerned here with the difference in electricity demand under the following conditions: electricity only space heating and combined electricity-wood space heating. In Fig. B.1, we present electricity demand for the estimated 1.609 million households with permanent electric space heating equipment in the Bonneville region, based upon the same households used in developing Table B.1.

As indicated in Fig. B.1, HRCP affected a certain reduction in demand (CRD). The difference between the top of line R to the top of line R^1 is CRD due to HRCP. In other words, under the heavy wood use condition electricity demand was reduced by at least CRD. However, we are presently concerned with the difference between this postretrofit demand level due to CRD and the postretrofit level of demand that might exist if there were no virtual conservation being practiced.

We developed two post hoc estimates of demand.* Line W represents pre- and postretrofit electricity demand for the heavy wood use space heating condition. Line E represents electricity demand for the electricity only space heating condition. (Please note that the point at which lines W, E, and A, the actual reduction in demand for all houses,

*Arguably, we assume that the submetered houses are representative of HRCP participants, which are representative of other communities in the BPA region.

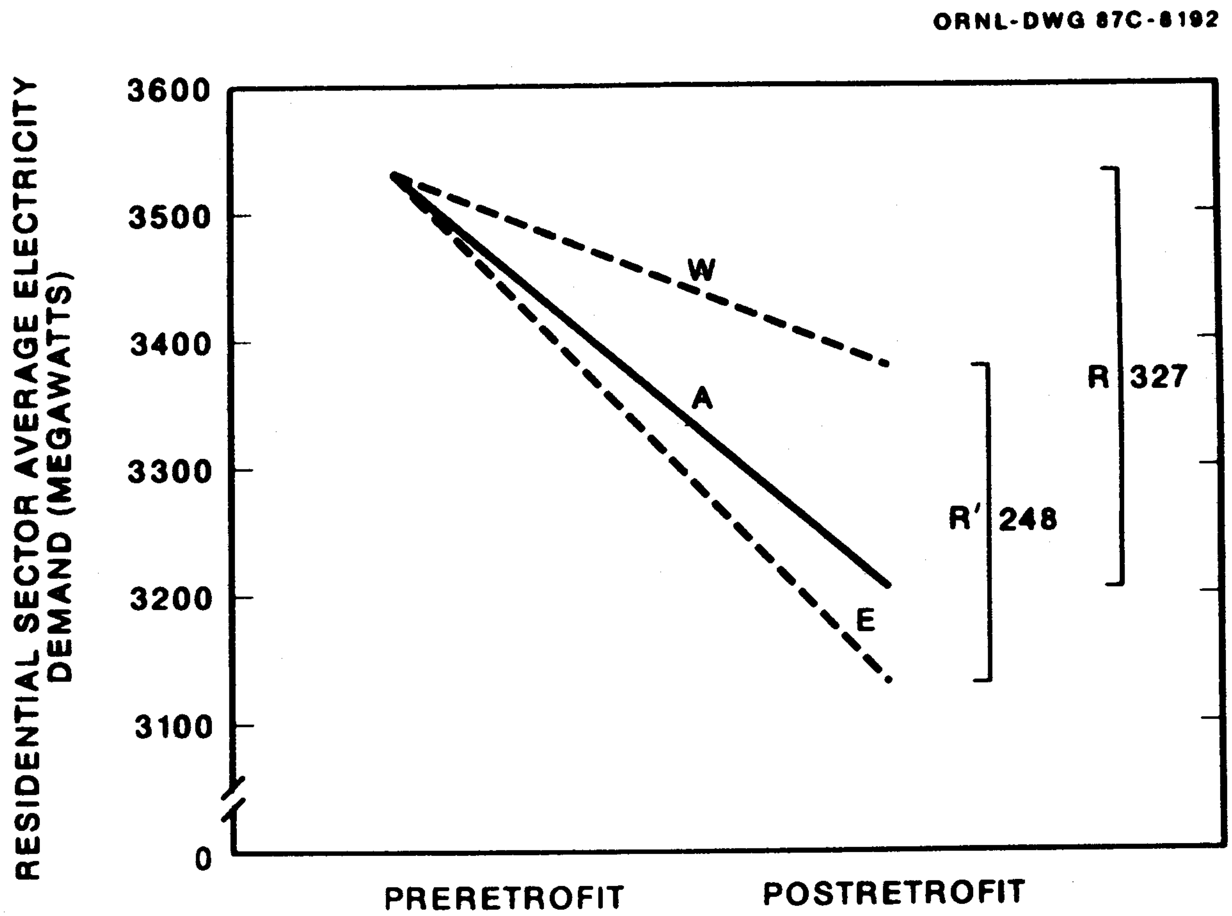

Fig. B.1 Estimated residential sector electricity demand (megawatts) based upon HRCP results, pre- and postretrofit.

join at the top left of Fig. B.1 represents the average electricity demand for all houses before retrofit.)

The difference, line R^1, between these two conditions represents the uncertainty that exists concerning residential electricity demand for space heating. In other words, residential electricity demand could fluctuate by R^1 as the population of homes switched heavily to wood and back to electricity to meet space heating needs. Line R represents the actual reduction in average electric space heating demand for all houses. Line R minus line R^1 divided by R multiplied by 100% is the range of uncertainty based upon the extreme cases.

The range of uncertainty is 15.7% of the preretrofit residential sector average electricity demand. In other words, demand could fluctuate by as much as R^1 (248 MW) as the population of households switch heavily to wood and back to electricity to meet space heating needs after retrofit. Since not all households heat exclusively with electricity and since wood is a common space heating fuel in the Pacific Northwest, such fluctuations could be significant and occur in time periods much shorter than periods required for new power resource construction or shutdown.

If Bonneville's goal is to treat conservation as an energy resource, then it seems that woodusers, and perhaps other fuel users, possess the potential to seriously disrupt even the best crafted power acquisition plans. When woodusers are properly considered in these measurements, power resources acquired due to conservation may not be as great but the risk of underestimating the concomitant change in demand can be reduced. As a consequence, the prospects for either energy shortfalls or idle power resources are minimized.

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