Analysis of End-Use Electricity Consumption During Two Pacific Northwest Cold Snaps

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The Pacific Northwest has experienced unusually cold weather during two recent heating seasons. Hourly end-use load data were collected from a sample of residential and commercial buildings during both cold snaps. Earlier work documented the changes in end-use load shapes as outdoor temperatures became colder. This paper extends analysis of electricity consumption in cold weather by comparing results from both cold snaps, exploring the variability of electricity consumption between sites, and describing the use of load shapes in simulating system load.

Load shapes from the first cold snap showed that hot water use shifted to later in the morning during extremely cold weather. This shift in water heat also occurred during the second cold snap and is similar to the shift observed on a typical weekend. Electricity consumption averaged across many sites can mask widely varying behavior at individual sites. For example, electricity consumption for space heat varies greatly between homes, especially when many homes are able to burn wood. Electricity consumption for space heat is compared between a group of energy-efficient homes and a group of older homes.

Introduction

Unusually cold winter temperatures were recorded in both the 1988/1989 and 1990/1991 heating seasons in the Pacific Northwest. Until recently, the Pacific Northwest was considered energy constrained only, and not capacity constrained with regard to electricity generation and transmission. Electricity consumption in the Puget Sound area, however, is now limited by transmission capacity across the Cascade Mountains during extremely cold weather.

The Bonneville Power Administration (Bonneville) began a study of peak electricity consumption after the 1988/1989 heating season to determine the potential of reducing peak loads with conservation and load management programs (Bonneville 1991). Much of the analysis is based on metered end-use load shapes collected by Bonneville's End-Use Load and Consumer Assessment Program (ELCAP). Having an end-use metering program in place during the two cold snaps provided valuable insights on energy consumption and load shapes in cold weather.

End-use load shapes from the second cold snap are compared to load shapes documented earlier from the first cold snap (Gillman, Sands, and Lucas 1990). This paper compares results from the two cold snaps and describes how this information was used to simulate system load. The energy performance of homes built to the Northwest Power Planning Council's Model Conservation Standards (MCS) is documented for both cold snaps. The following sections also provide a discussion of daily average energy consumption in cold weather, load shape impacts, and the variability of electricity consumption across homes.

Weather Comparisons

Daily high and low temperatures for Seattle during both cold snaps are shown in Figure 1. During the first cold snap, the day with the lowest average daily temperature was February 3, although the coldest temperature occurred on February 4. December 21, 1990, was the coldest day during the second cold snap. Electricity consumption peaked on February 3, 1989, and on December 21, 1990, which were both Fridays.

Winter weather data for Seattle and two other cities are provided in Table 1. Weather is much colder east of the Cascade Mountains than in Seattle or Portland. Note that temperatures during the two recent cold snaps were not record lows, implying that record cold temperatures would bring even greater peak loads.

February 3, 1989, and December 21, 1990, were considered "extreme peak days" for analysis documented in the Puget Sound Area Electric Reliability Plan (Bonneville 1991). Peak days from two other heating seasons (February 2, 1988, and February 14, 1990) were called "normal peak days," or the coldest days to occur during typical heating seasons. None of the peak days in

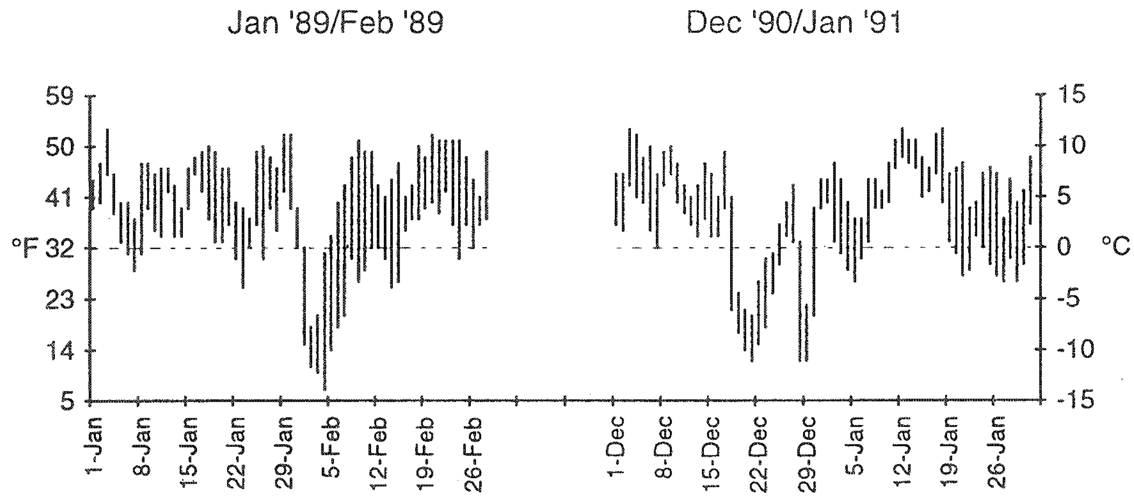

Figure 1. Daily Temperature Ranges for Seattle

these four heating seasons were in January, even though January is colder, on average, than any other month.

Daily Energy Comparisons

This section documents the performance of a sample of MCS homes for both cold snaps. Daily energy consumption for space heat is modeled as a function of average outdoor temperature for groups of MCS and non-MCS homes.

Performance of MCS Homes

Energy planners in the Pacific Northwest are very interested in the performance of homes built to the MCS. Daily electricity consumption for space heat during the first cold snap (February 1989) is shown in Figure 2. Space heat consumption is measured in units of average kW over 24 hours. Base sites are from the ELCAP sample, and are generally older and not as energy efficient as MCS homes. A similar plot for the second cold snap (December 1990) is shown in Figure 3. The ELCAP sample has decreased in size in the two years between cold snaps.

Table 1. Winter Temperatures in the Pacific Northwest
Degrees Fahrenheit (Degrees Celsius)

		Seattle		Spokane		Missoula	
Normal Daily Max. in January		44	(7)	31	(-1)	29	(-2)
Normal Daily Min. in January		34	(1)	20	(-7)	14	(-10)
Record Low		0	(-18)	-25	(-32)	-33	(-36)
Heating Season:	1987/1988 Low	25	(-4)	-5	(-21)	-13	(-25)
	1988/1989 Low	10	(-12)	-11	(-24)	-23	(-31)
	1989/1990 Low	22	(-6)	2	(-17)	-2	(-19)
	1990/1991 Low	12	(-11)	-16	(-27)	-28	(-33)

Source: National Oceanic and Atmospheric Administration

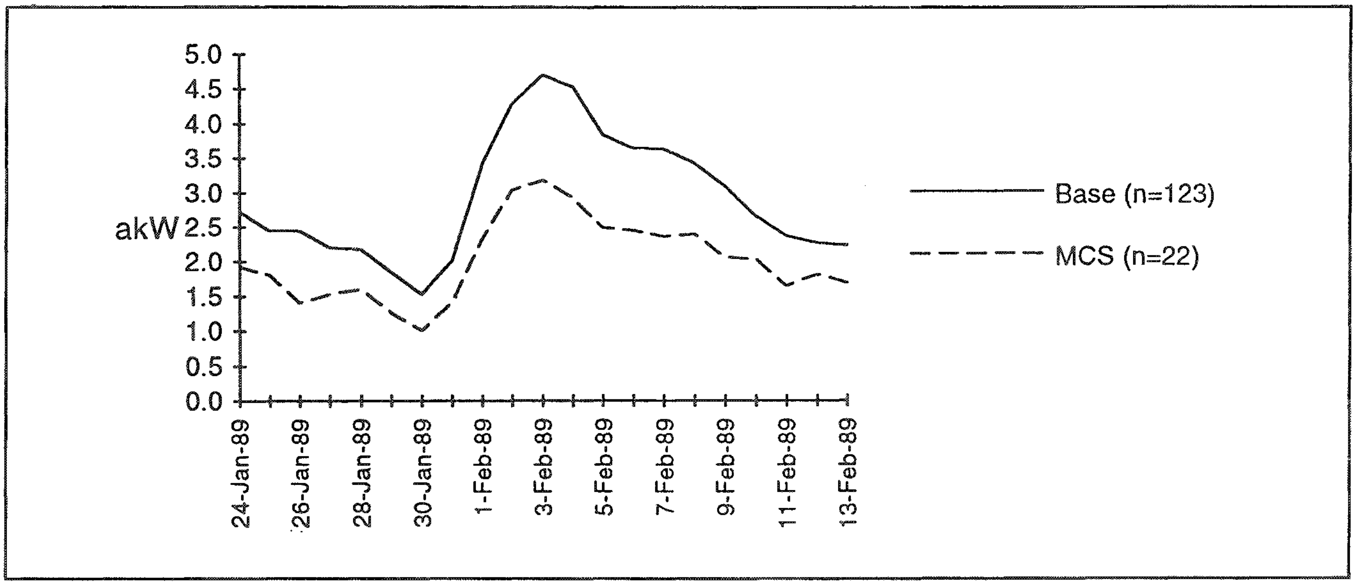

Figure 2. Daily Electricity Consumption for Space Heat - First Cold Snap

Figures 2 and 3 show that MCS homes continue to perform well in terms of daily space heat consumption, with savings increasing as temperatures fall. Figures 2 and 3 are both set up around a 21-day data window, ten days on either side of the system peak day. For a site to be included in Figure 1 or Figure 2, observations on average daily space heat consumption were required for 20 of the 21 days. Sample size would have been smaller if daily observations had been required for all 21 days for all sites. In Figure 2, the difference in daily electricity consumption for space heat is 1.51 average kilowatts (akW) on February 3, 1989. Figure 3 shows a difference of 1.57 akW on December 21, 1990.

The homes used in this analysis should not be considered as statistically representative of all homes in the Pacific Northwest. The results presented here show how two groups of homes respond to cold weather. There are many other factors affecting electricity consumption, such as wood-burning equipment and size of home, which were not controlled for.

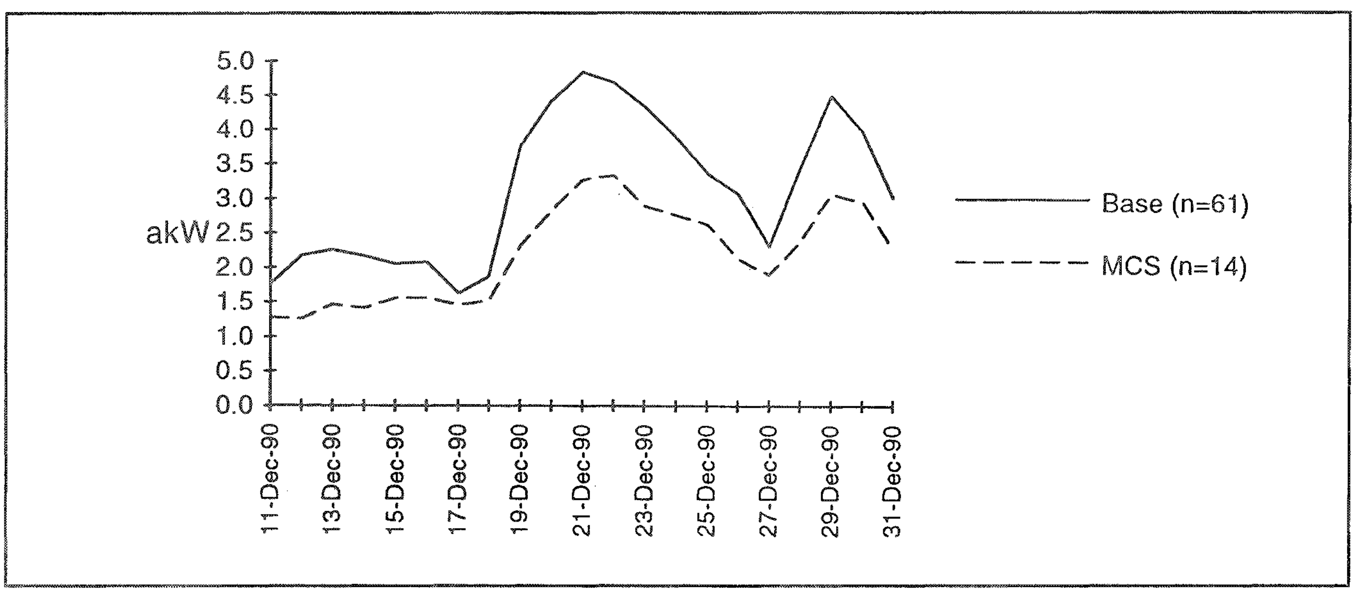

Figure 3. Daily Electricity Consumption for Space Heat - Second Cold Snap

Data plotted in Figures 2 and 3 are averages across sites and do not show the variability of space heat consumption across sites. The histogram in Figure 4 puts daily electricity consumption for space heat into categories based on consumption in average kilowatts. For example, the second category includes homes that used at least 1.0 akW, but less than 2.0 akW.

Electricity consumption for space heat in MCS homes on February 3, 1989, is close to a bell-shaped curve centered near 3.0 akW per home. The distribution for base sites is quite different, with many homes using very little electricity for space heat and several homes with very large consumption. All of the base sites have permanent electric space heating systems, but many can also burn wood. Average electricity consumption for the base homes in Figures 2 and 3 would have been greater if wood-burning homes had been excluded. Table 2 shows how wood-burning equipment is distributed among the sample of base and MCS homes from the first cold snap. A larger portion of base homes have wood-burning equipment than do MCS homes.

Space Heat Response to Outdoor Temperature

Observations on daily space heat consumption can be combined with daily weather observations to model the response of space heat to outdoor temperature. For homes that heat only with electricity, the relationship between electricity consumption for space heat and average outdoor temperature is close to linear during winter months. If end-use data had not been available for extremely cold days, peak electricity consumption would have been estimated for those days by linear extrapolation from the coldest days available. ELCAP data provided actual observations on end-use electricity consumption during extremely cold weather, reducing the uncertainty in models of peak electricity consumption.

Many homes in the Pacific Northwest burn wood. Space heat electricity consumption is not a linear function of average outdoor temperature in these homes because electricity or wood, or some of each, can be used on any given day. Consequently, space heat consumption for individual homes can be difficult to model.

It is easier to model space heat consumption for groups of homes, thus reducing the scatter created by wood-heated homes. Figures 5 and 6 show the mean response of daily space heat consumption in ELCAP homes to average outdoor temperature. ELCAP homes were split into groups east and west of the Cascade Mountains, and the MCS homes were plotted separately. For each day, both temperatures and electricity consumption for space heat were averaged across sites. Winter temperatures are much lower east of the Cascade Mountains than on the west side.

In both Figure 5 and Figure 6, the group of MCS homes consumes less electricity for space heat than do the base homes at any given average outdoor temperature. A straight-line fit for each group of observations would provide a linear relationship for simulating space heat

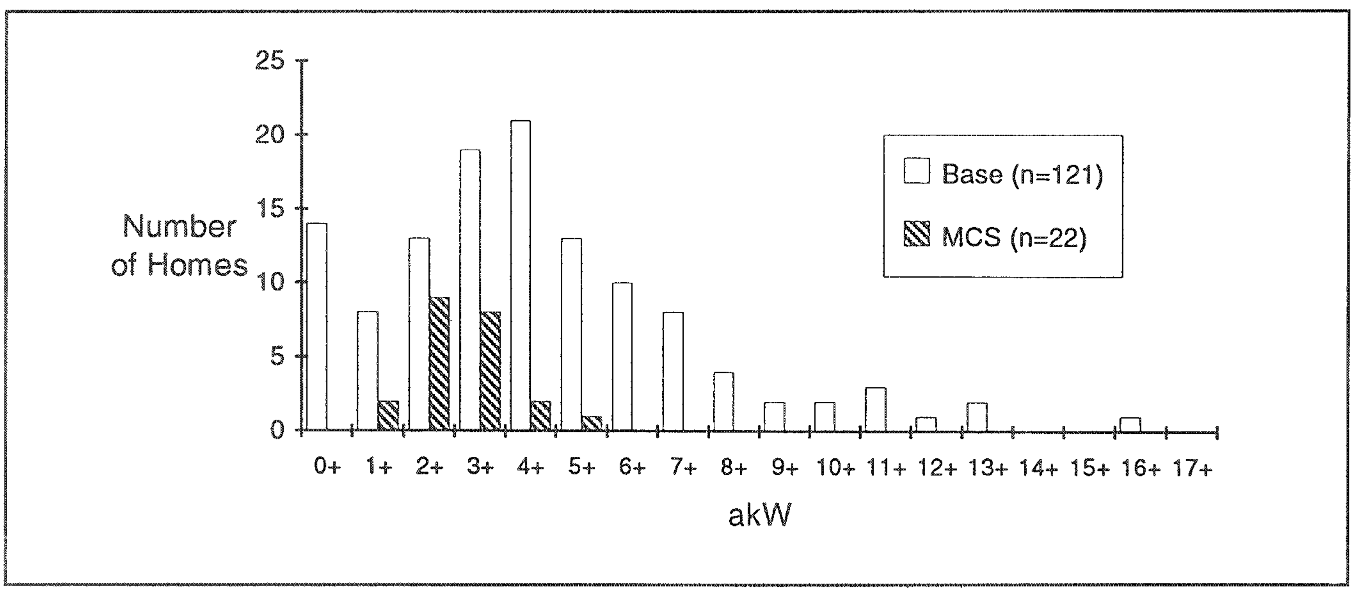

Figure 4. Distribution of Daily Electricity Consumption for Space Heat - February 3, 1989

Table 2. Availability of Wood Burning Equipment (Number of Homes)

	Base Homes	MCS Homes
None	24	12
Minor (Fireplace)	36	8
Major (Fireplace Insert or Wood Stove)	63	1

electricity consumption. Electricity consumption could then be estimated for even colder temperatures, or for an increasing ratio of MCS to non-MCS homes. Over time, it is expected that homes built to the MCS will be a growing fraction of homes in the Pacific Northwest.

Load Shape Analysis

Winter electricity consumption in the residential sector is broken down into three end uses: space heat, water heat, and miscellaneous. It has proven useful to simulate peak electricity consumption by end use on three day types (Bonneville 1991).

Average Winter Weekday. Load shapes for non-holiday weekdays are averaged across days in January by hour.

Normal Peak Day. The coldest day to occur in a typical heating season. February 2, 1988, and February 14, 1990, were used as normal peak days.

Extreme Peak Day. The coldest day thought to occur once in every 10 or 20 years. February 3, 1989, and December 21, 1990, were considered extreme peak days. These were not necessarily the coldest days at all weather stations in the Pacific Northwest, but system load did peak on these days.

Space Heat Load Shapes

Space heat load shapes for three day types are shown in Figure 7 for a sample of 50 ELCAP base homes in the Pacific Northwest, with December 21, 1990, as the extreme peak day. These homes include a variety of heating systems, including baseboard and central forced air.

It is difficult to make any general conclusions about these space heat load shapes except that electricity consumption increases at all hours as the temperature falls, and the extreme peak day had a higher load factor than the other

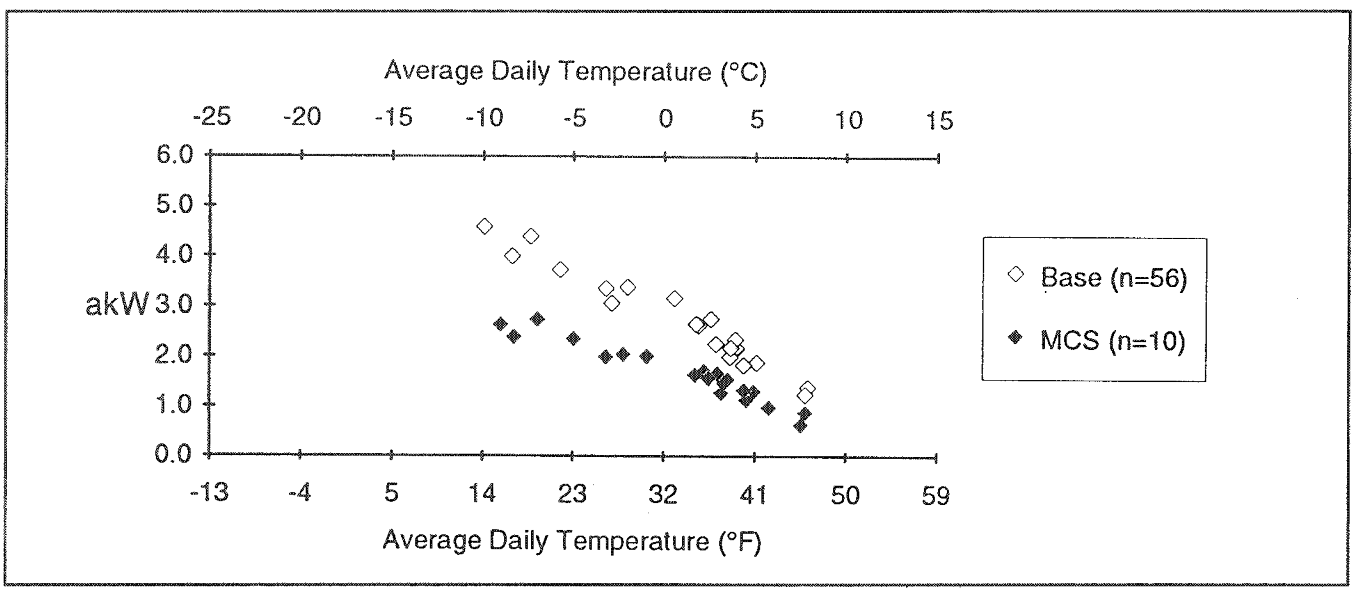

Figure 5. Aggregate Response Curves in First Cold Snap - West of Cascade Mountains

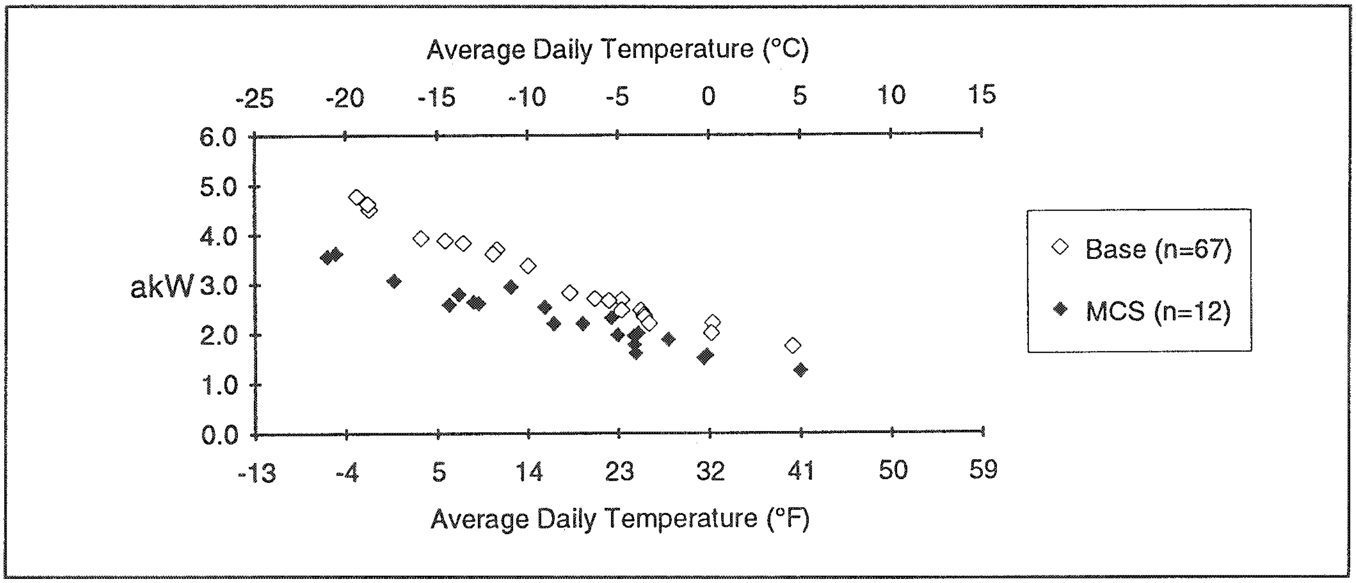

Figure 6. Aggregate Response Curves in First Cold Snap - East of Cascade Mountains

two day types. This change in load factor for residential space heat was not as great as observed during the first cold snap (Gillman, Sands, and Lucas 1990).

As was seen in the histogram in Figure 4, averages across sites mask widely varying levels of energy consumption, especially in the ELCAP base sample. In addition to different levels of consumption, there is also variation in thermostat setback behavior between sites, resulting in a wide variety of space heat load shapes for individual homes.

Water Heat Load Shapes

Water heat load shapes were used to estimate peak savings from a proposed water heat control program in the Puget Sound area (Bonneville 1991). On typical winter weekdays, peak load for water heat occurs during the same hour as system peak, between 7:00 a.m. and 8:00 a.m. This pattern still holds for peak days during a typical winter. The pattern changes, however, during extremely cold weather, with both water heat and system load

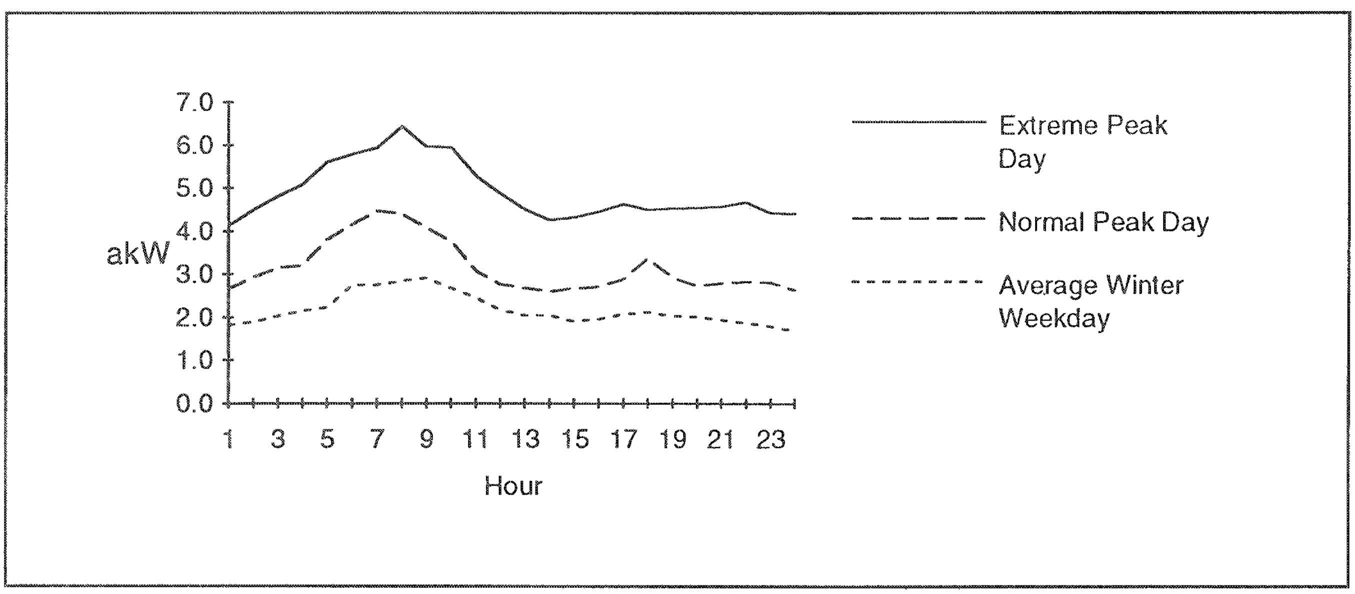

Figure 7. Space Heat Load Shapes for Three Day Types

Table 3. Daily Load Factors for Residential End Uses

Day Type	Space Heat	Water Heat	Misc.
Extreme Peak Day (December 21, 1990)	0.766	0.527	0.706
Normal Peak Day (February 14, 1990)	0.710	0.427	0.715
Average January Weekday	0.746	0.460	0.661

peaking later in the morning. The shift in water heat load is likely due to the school and business closures that may occur during extreme weather. Figure 8 displays a sequence of water heat load shapes for a typical Thursday-Friday-Saturday in winter. Water heat load peaks during hour 8 on Thursday and Friday, but peaks much later on Saturday morning.

During a cold snap, the water heat load shape on an extreme peak day starts to look like a Saturday load shape. Water heat load shapes for three day types are shown in Figure 9. The average January weekday and normal peak day (February 14, 1990) both peak during hour 8. The extreme peak day (Friday, December 21, 1990) looks very much like a Saturday load shape. This pattern also appeared during the first cold snap, where February 3, 1989, was the extreme peak day (Gillman, Sands, and Lucas 1990).

Because of the shift in water heat load shapes, peak savings for a water heat control program may be reduced on extreme peak days, when the savings are needed most. Load shapes shown in Figures 8 and 9 are averages across sites, and represent load shapes seen by the electrical distribution system. Water heat load shapes for individual sites are quite different, with the water heater either on or off (Pratt and Ross 1991). When the water heater is on, electricity consumption is approximately 4.0 kilowatts per tank.

Miscellaneous Load Shapes

The miscellaneous end use includes everything except space heat, air conditioning, and water heat. Load shapes for three day types are shown in Figure 10. The extreme peak day load shape appears to be shifted upward at all hours compared to the other two day types. During the first cold snap, increased consumption was concentrated around the noon and evening hours (Gillman, Sands, and Lucas 1990).

System Load Shapes

Four system load shapes are shown in Figure 11: two extreme peak days, one normal peak day, and one typical winter weekday. The normal peak day is February 14,

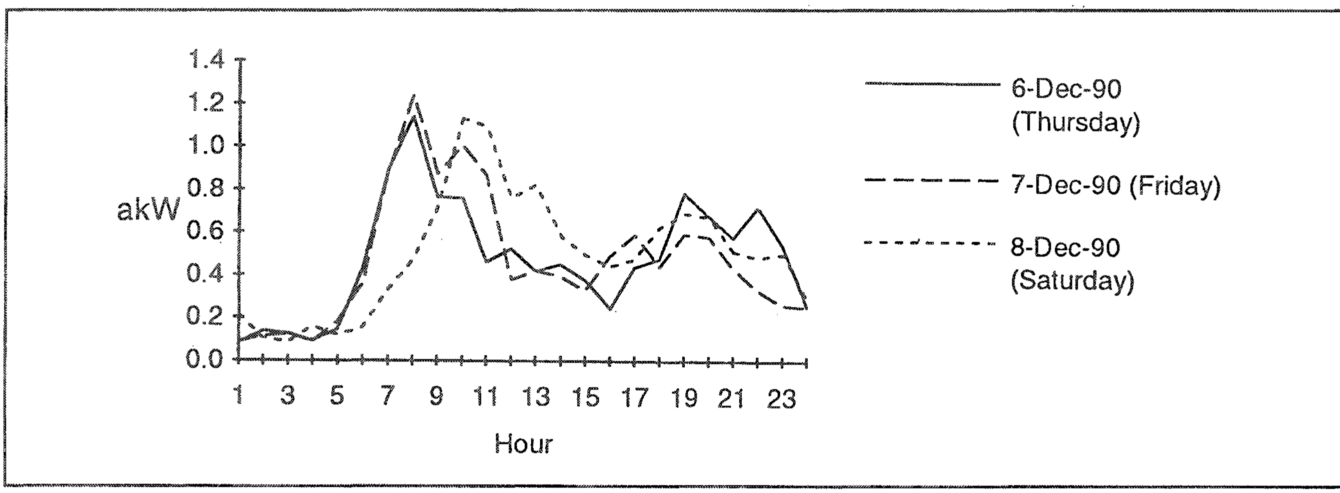

Figure 8. Typical Water Heat Load Shapes: Thusday-Friday-Saturday (n=82)

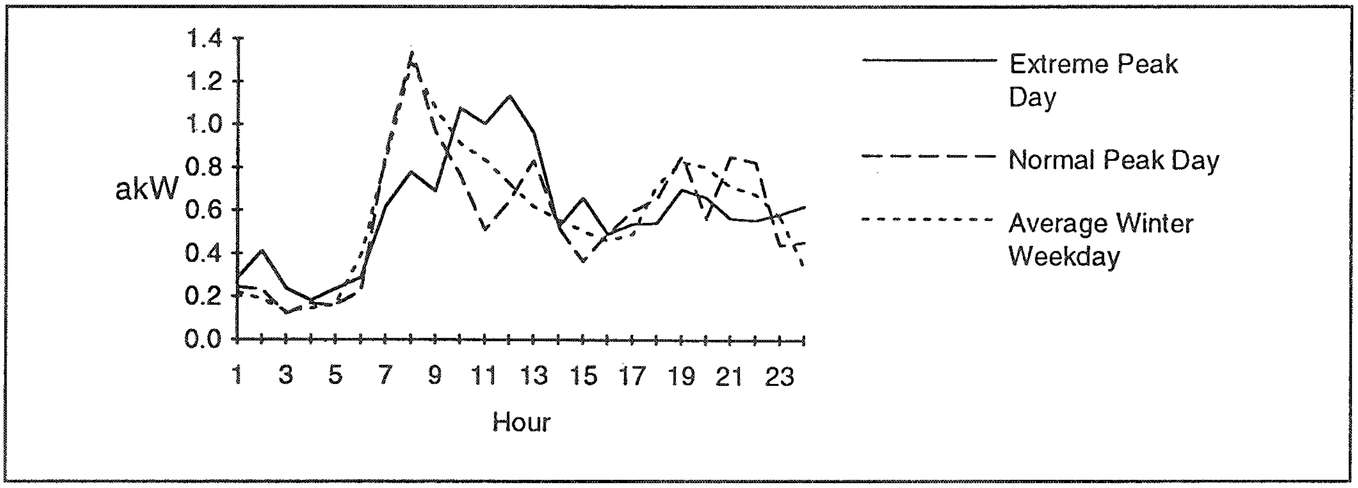

Figure 9. Water Heat Load Shapes for Three Day Types

1990. Friday, December 7, 1990, is used to represent a typical winter weekday. System peak occurs one hour later in the morning on the two extreme peak days than on the other two day types. Each hourly observation is average power across one hour. For example, hour 9 is an average of electricity consumption from 8:00 a.m. to 9:00 a.m. Data shown in Figure 11 are actual hourly observations for the Pacific Northwest electrical distribution system.

Load shapes for the two extreme peak days are very similar, with system peak occurring at hour 9. Electricity consumption remains high for several hours after the morning peak on the extreme peak days. Load shapes for the normal peak day (February 14, 1990) and the typical winter weekday (December 7, 1990) are similar in that they both peak at hour 8. Daily load factors for these four load shapes are shown in Table 4, with the highest load factors occurring on extreme peak days.

System load includes the residential sector, and the system shape shows some of the same patterns seen in residential end uses. On an annual basis, residential electricity consumption is about one-third of system load. This fraction is greater on cold days because the residential sector is relatively more weather sensitive than the rest of the system. Load factors are higher on extreme peak days in both the system load shape and residential end-use load shapes. On extreme peak days, system peak is shifted to later in the morning and remains close to the peak for several hours. Some of this shift may be due to the shift in residential water heat.

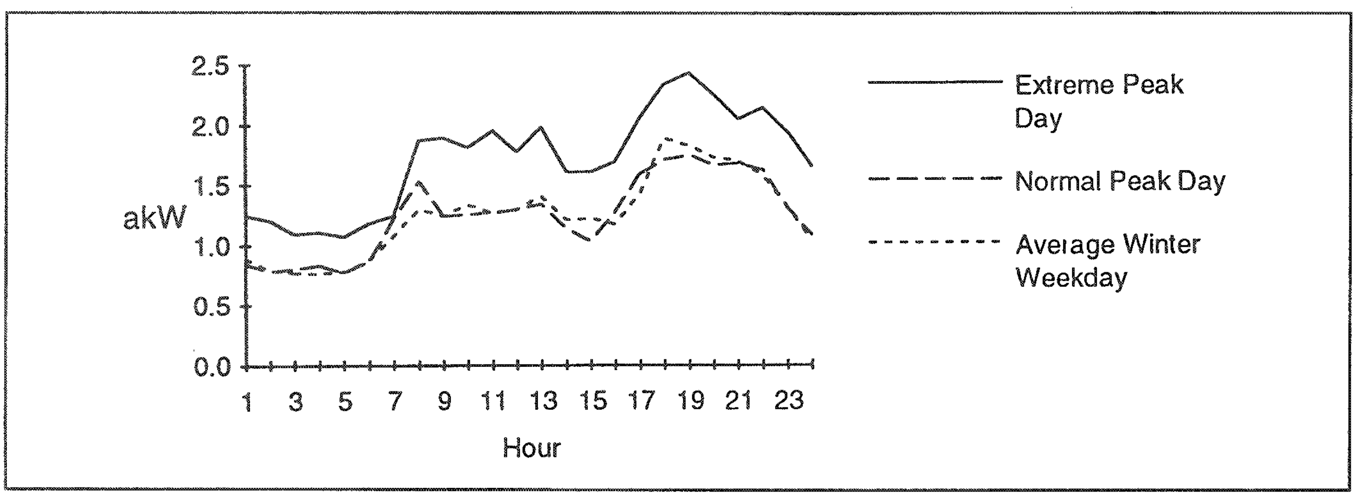

Figure 10. Miscellaneous Load Shapes for Three Day Types

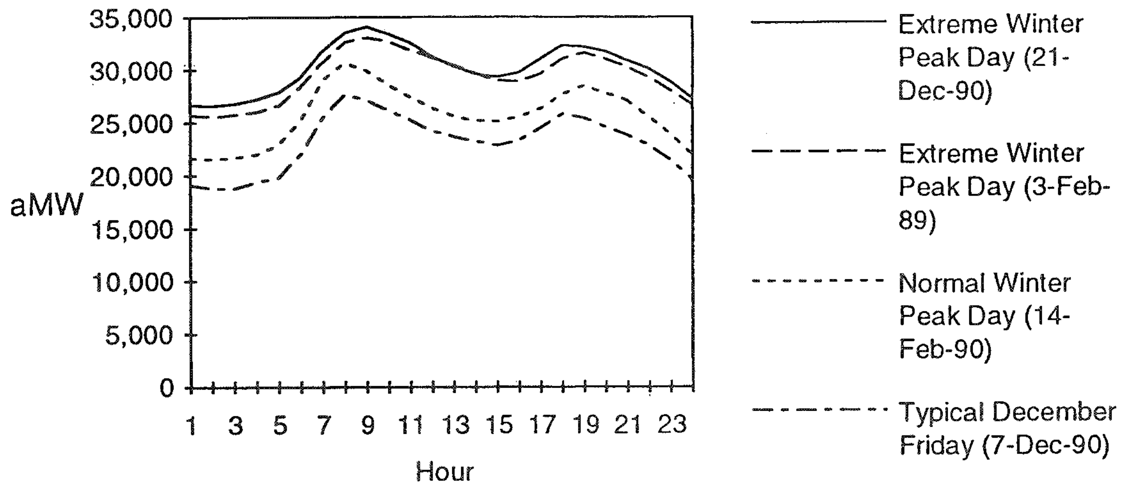

Figure 11. Pacific Northwest System Load Shapes

Both water heat and system load shifted to later in the morning on extremely cold days. A water heat control program would still have a large impact on system load, since both load shapes shift in the same direction.

Peak Load Simulation

Peak electricity consumption was modeled for the Puget Sound Area Electric Reliability Plan (Bonneville 1991) so that the effect of conservation and load management on winter peaks could be estimated. Metered ELCAP data provided essential information on the timing and magnitude of peak loads at the end-use level. The following steps were used to create a baseline forecast of hourly electricity consumption on cold days. These steps can be applied to summer peaks as well as winter peaks.

1. Forecasts of annual electricity consumption by end-use, in annual average megawatts (aMW), were obtained from a forecast produced jointly by Bonneville and the Northwest Power Planning Council.

2. Annual electricity consumption was broken down into monthly consumption for major end-uses in the residential and commercial sectors using historical ELCAP data. This provided average end-use electricity consumption for a typical day in any desired month.

3. Scale factors were created using ELCAP data to convert electricity consumption on an average January day to an extremely cold day. This provides average daily electricity consumption for peak winter days. For the Puget Sound Area Electric Reliability Plan, scale factors were simply ratios of metered electricity consumption on different day types. An alternative method is to derive a linear relationship between

Table 4. Daily Load Factors for System Load Shapes

Day Type		Load Factor
Extreme Peak Day	(December 21, 1990)	0.885
Extreme Peak Day	(February 3, 1989)	0.889
Normal Peak Day	(February 14, 1990)	0.838
Typical Winter Day	(December 7, 1990)	0.837

average daily temperature and electricity consumption for space heat. A straight-line fit to the data in Figures 5 and 6 would provide such a relationship.

4. End-use load shapes were used to distribute daily electricity consumption across 24 hours. This provided hourly forecasts by end-use for selected day types.

Conclusions

A second cold snap in three heating seasons provided the opportunity to compare end-use electricity consumption between two similar cold snaps. Of special interest was the performance of homes built to the Model Conservation Standards.

1. MCS homes performed very well in terms of daily electricity consumption for space heat relative to non-MCS homes. Results for both cold snaps were very similar, even with a smaller sample size in the second cold snap.

2. During the first cold snap, it was observed that water heat load shifted to later in the morning on extremely cold days. The same pattern was present in the second cold snap and is similar to water heat load on a Saturday.

3. System load shapes peaked one hour later on extremely cold days than on typical winter days. This occurred during both cold snaps. Behavior of end-use load shapes in the residential sector helps explain the shift in system load on extremely cold days.

4. The methodology described here to simulate peak electricity consumption on cold winter days might work just as well on hot summer days. The three day types of interest would be a typical summer day, the warmest day in a typical summer, and an extremely hot day. One current application is the impact of global climate change scenarios on summer and winter peaks in the Pacific Northwest.

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Endnote

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