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Residential Retrofit Measures in the Hood River Conservation Project: Recommendations, Installations, and Barriers

Richard Goeltz
Eric Hirst

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CONTENTS

SUMMARY

The Hood River Conservation Project (HRCP) is a major residential retrofit demonstration project. HRCP is funded by the Bonneville Power Administration and run by Pacific Power & Light in cooperation with the Hood River Electric Cooperative. The Project was conducted in the community of Hood River, Oregon, will cost $21 million, and last for three years (mid-1983 through 1986). Installation of applicable retrofit measures was completed by the end of 1985; data collection and analysis will continue through 1986. The project sought to install as many cost-effective retrofit measures in as many electrically-heated homes in Hood River as possible. HRCP planning, implementation, and analysis are guided by a Research Advisory Group, whose members represent the major participants in the project.

HRCP offered a package of "super" retrofit measures. The Project paid for installation of these measures up to a cost-effectiveness limit of $1.15/first-year estimated kWh saved, roughly four times the limit in other residential retrofit programs. Thus, HRCP will identify levels of installation when cost to the household and prior retrofit activities are largely eliminated as barriers. This will help define the maximum reasonable market penetration of residential retrofit as an energy resource in the Pacific Northwest.

This report documents the extent to which measures included in the Project were recommended and installed in participant homes. The report also examines the reasons for noninstallation of measures, the barriers between potential and practice. These analyses are based on data from the 3249 homes that had some contact with HRCP (of which 3189 received home energy audits). This represents more than 90% of the eligible electrically-heated homes in Hood River.

The major findings from this study are:

1. Conservation potential can be defined in several ways. For example, the potential could hypothetically assume that every retrofit measure can be installed in every home. Alternatively, the potential could include only those measures recommended during an energy audit as compatible with the structure and its heating system, physically feasible, and cost-effective.

   Consider the first definition of potential. Averaged over all the measures and homes in this analysis, 46% of the 15 measures theoretically available in the HRCP package were installed by HRCP, 45% of the measures were neither recommended nor installed, and 9% were recommended but not installed (Fig. S-1).

   The second definition paints a different picture. Eighty-three percent of the measures recommended in the energy audits were installed by HRCP. These installed measures yielded an estimated saving of 6140 kWh/year (93% of the estimated saving for all the recommended measures). Although 17% of the recommended measures were not installed, only 7% of the estimated electricity savings were not realized.

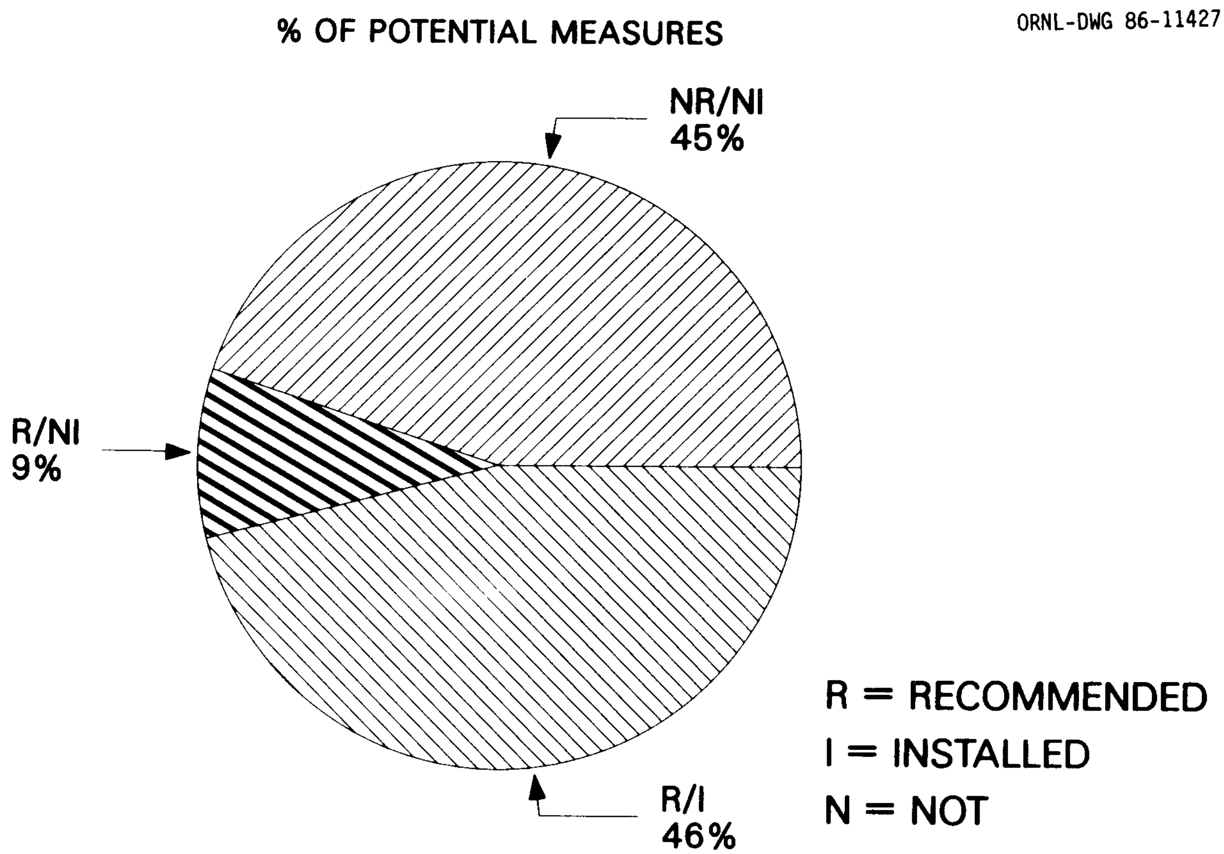

Fig. S-1. Distribution of HRCP measures (15 measures times 3249 homes), by recommendation and installation.

2. Only 8% of the homes had no major measures installed by the Project, which explains some of the difference in potential realized, noted above. The barrier identified most frequently (in 56% of these 261 homes) was lack of cost-effectiveness. This suggests that these homes had installed applicable retrofit measures prior to HRCP, either on their own or through participation in earlier conservation programs. For example, 25% of these homes had participated in prior utility retrofit programs; only 8% of the other HRCP participants had participated in these programs.

3. The cost-effectiveness limit for HRCP installation of retrofit measures was $1.15/first-year estimated kWh saving. However, the total HRCP cost, averaged across the completed homes that had at least one major retrofit measure installed, was only 69¢/kWh, which suggests that most of the savings were achieved at much less than the maximum allowable cost.

4. The average cost of HRCP-installed retrofit measures was $3760, of which HRCP paid 99%. Only 10% of the households paid anything for HRCP-installed measures; their average payment was $430.

5. Single-family homes accounted for 60% of the HRCP participants. Because these dwelling units are substantially larger than multi-family units and mobile homes, their estimated energy savings and retrofit costs were much higher. The estimated savings per unit floor area were much higher for single- and multi-family units than for mobile homes; apparently, only limited opportunities exist to retrofit mobile homes.

6. HRCP retrofit costs and estimated savings increased with house age. For example, the savings and retrofit costs were roughly three times higher for homes constructed before 1945 than for homes built during the 1980s. Improvements in construction practices, stimulated by higher fuel prices and by new construction standards, reduced the potential for retrofits in newer homes.

7. There was substantial variation across measures in the frequency of recommendation and installation. Ceiling insulation, storm windows, caulking, door weatherstripping, and outlet gaskets were installed in more than two-thirds of the homes. On the other hand, duct insulation and thermal doors were installed in less than 15% of the homes.

8. The four insulation measures (ceiling, wall, floor, heating ducts) accounted for 57% of the total estimated savings and 48% of the total retrofit cost. Thus, these measures dominated energy savings and were relatively cost-effective. The three window and door measures, however, were relatively expensive, accounting for only 27% of the estimated savings but 47% of the cost. The eight infiltration reduction, water heating, and clock thermostat measures were both inexpensive and small energy savers.

9. The reasons that HRCP measures were not installed were grouped into a few categories (Fig. S-2). Almost half (45%) of the barriers that prevented installation arose because the measure was already partially or fully in place, which rendered further installation cost-ineffective. Physical barriers accounted for 31% of the noninstallations, noncompatible conditions for 19%, customer concerns for 4%, and other barriers for the remaining 2%.

10. The vast majority (81%) of the barriers were identified during the energy audit. Small fractions were uncovered later, during the contractor bid, installation, or inspection phases of the Project. Thus, the energy auditors did a careful job of identifying barriers to installation of retrofit measures.

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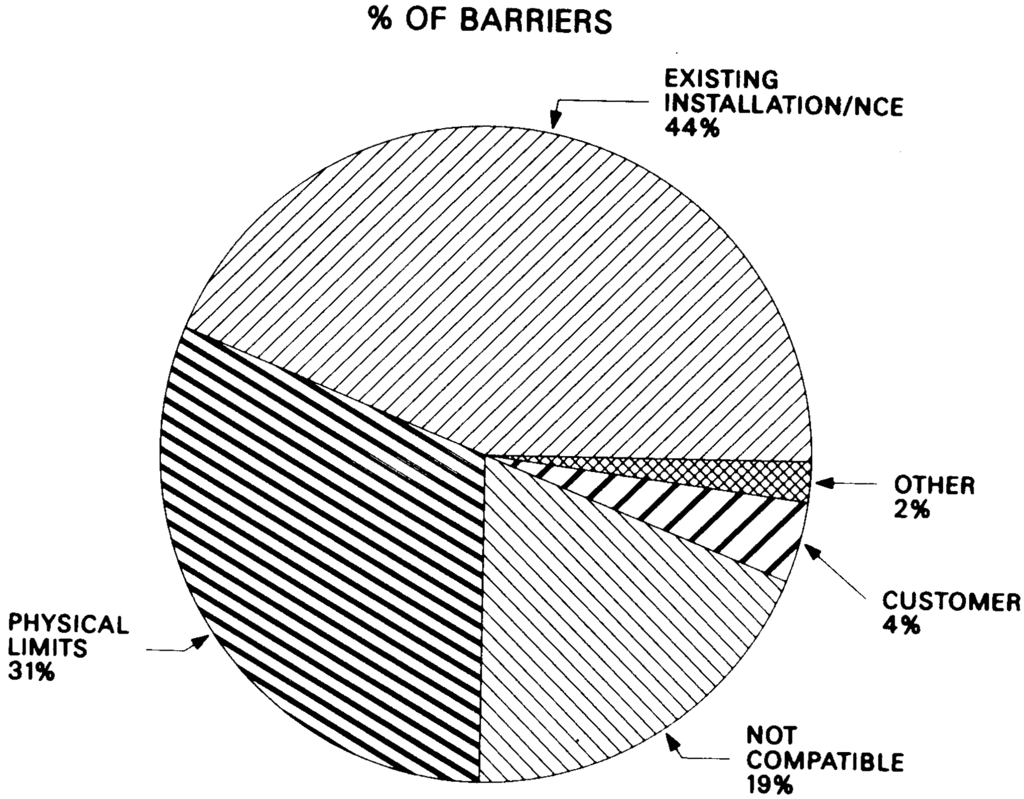

Fig. S-2. Distribution of barriers for HRCP measures not installed, by type of barrier. (NCE is not cost effective.)

LIST OF ACRONYMS

AAHX	air-to-air heat exchanger
BPA	Bonneville Power Administration
Council	Northwest Power Planning Council
HRCP	Hood River Conservation Project
HREC	Hood River Electric Cooperative
NCE	not cost-effective
NRDC	Natural Resources Defense Council
NWPPA	Northwest Public Power Association
ORNL	Oak Ridge National Laboratory
PNUCC	Pacific Northwest Utilities Conference Committee
PP&L	Pacific Power & Light Company
RWP	Residential Weatherization Program

1. INTRODUCTION

The ultimate success of a conservation program depends on the fraction of eligible customers who participate in the program, the fraction of recommended conservation actions adopted by these participants, and the actual energy savings achieved by the adopted measures and practices. Because program effectiveness is a multiplicative (rather than additive) function of these three factors, the actual performance of government and utility conservation programs is generally very much less than their potential.

A successful program, for example, might reach 50% of its potential market and induce these participants to adopt 50% of the recommended actions. If these actions yield energy savings that average 75% of the engineering predictions, then the overall program savings are only 14% (0.50 x 0.50 x 0.75) of its estimated potential.

In practice, many eligible customers choose not to participate in a particular program: they may not know about the program, they may lack funds to pay for the recommended actions, they may believe that their building is already energy-efficient, they may plan to move soon, they may not own their home, or they may be too busy to take time for conservation actions.

Several reasons cause customers who participate in a program not to adopt recommended actions: the building may already contain some of the measures offered by the program, some measures may not be applicable to the particular home, the cost of some measures may be too high, the customer may believe that estimated savings will not be achieved, or the customer may not like the measures.

The actual energy savings realized after adoption of recommended actions might be less than anticipated for several reasons: poor quality of measures, poor workmanship during installation, interactions among various conservation measures, and operational changes that offset some of the energy savings (e.g., reduced use of wood for space heating or increased indoor temperatures in winter after retrofit).

The Hood River Conservation Project (HRCP) affords a unique opportunity to examine the differences between potential and practice for each of these three factors. HRCP is an experimental residential retrofit project, operated by Pacific Power & Light Company (PP&L) and funded by the Bonneville Power Administration (BPA). The project sought to install as many cost-effective retrofits as possible in all electrically heated homes in the community of Hood River, Oregon.

The program offered a comprehensive package of 15 retrofit measures at very high levels of installation [e.g., R-49 ceiling insulation rather than the R-38 that is recommended in BPA's Residential Weatherization Program (RWP)]. HRCP paid for installation of these measures up to a cost-effectiveness limit ($1.15/first-year estimated kWh saving; PP&L 1982) that is almost four times the limit in BPA's RWP. The free installation and high level of retrofit measures provide the opportunity to examine levels of implementation when cost to the household and existing levels of conservation measures are largely removed as obstacles. Thus, HRCP will help determine the maximum reasonable market penetration of residential weatherization as an energy conservation resource in the Pacific Northwest.

The purpose of this report is to document the extent to which measures included in the Project were recommended and installed in participant homes. In addition, we examine the reasons for noninstallation of measures, the barriers between potential and practice. As far as we know, HRCP is the first project to collect data on the reasons that measures are not recommended and not installed.

It is important to recognize that many definitions of "potential" and "barrier" are possible. The most inclusive definition of potential would refer to installation of the maximum amount of every measure in every house. This unrealistic definition assumes that existing homes presently have no energy-conserving devices in them. Barriers then explain why the measures actually installed fall short of this ultimate (and unrealistic) potential.

An alternative definition includes only those measures that can be installed, where "can" means physically possible. This definition excludes cases where the measure is already fully installed and cases where installation is not feasible (e.g., attic insulation in a cathedral ceiling, heating duct insulation in a house with room electric space heaters). In this definition, barriers explain why these feasible (in an engineering sense) measures are not installed.

The potential could also be defined in terms of measures whose installation is both technically feasible and economical. This definition would reduce the potential further by excluding from consideration those measures whose high installation cost and/or low expected energy saving make them not cost-effective (NCE).

In addition to the physical and economic barriers discussed above, other reasons cause measures not to be installed. A third major class of barriers relates to the household and includes aesthetics, inconvenience, perceived ineffectiveness of measures, and other customer concerns that prevent installation of recommended measures.

Finally, the potential could be defined in terms of a target level of energy efficiency. For example, a goal of X kWh/ft^2-HDD could be set for each home.

These comments suggest that the definition of "potential" is not simple. One can examine differences between potential and actual installations in many ways, depending on the definition chosen and perspective adopted. The HRCP data permit analysis from various viewpoints.

The following chapter briefly describes HRCP and the data available for evaluation purposes, with particular attention to the data used in this portion of the HRCP evaluation. Chapters 3 and 4 present results on the recommended and installed retrofit measures, and on related energy savings and retrofit costs. Chapter 3 discusses aggregate savings identified during the energy audits and reflected in the measures actually installed by the Project. Chapter 4 examines recommendations, installations, and the reasons for noninstallation on a measure-by-measure basis. The final chapter discusses results.

ORNL's responsibility for evaluation of HRCP includes answering several questions:

- What are the actual electricity savings (kWh) that can be attributed to the HRCP-installed measures and to HRCP itself?
- What are the actual electricity savings for individual measures? How do actual and estimated (audit) savings compare?
- To what extent do eligible households participate in the Project?
- To what extent are individual measures recommended and/or installed by the Project (penetration of measures)?

- What are the physical, behavioral, and economic barriers to implementation of these retrofit measures?

- What are the capacity (kW) effects due to implementation of the Project?

We plan to publish five reports this year, of which this is the first. A report examining program participation (the first of the three factors discussed on page 1) will be completed in mid-1986. Reports on actual electricity savings and on load reductions (kWh and kW effects, respectively; the third factor) will be published in Fall 1986. Finally, we will prepare a comprehensive report summarizing all ORNL and other HRCP research projects (Oliver et al. 1986).

2. THE HOOD RIVER CONSERVATION PROJECT AND RELATED DATA

THE PROJECT

HRCP is a major demonstration program designed to determine and document the extent to which "conservation energy resources" can be obtained from retrofits of existing homes. HRCP is intended to define the maximum limits of a utility-operated residential retrofit program, one in which cost to the household is not a barrier and in which the number and level of retrofit measures installed are beyond that usually included in such programs (PP&L 1983).

The three-year study is an outgrowth of the Pacific Northwest Electric Power Planning and Conservation Act (U.S. Congress 1980). This legislation established the Northwest Power Planning Council (Council) to develop a 20-year plan for the Pacific Northwest region's electricity demand and supply. Conservation was established, within the Act, as a cornerstone of this plan. In particular, conservation resources were given a 10% "bonus" in assessing the relative benefits and costs of conservation resources, traditional supply resources, and unconventional supply resources. Unfortunately, much of the information needed to define the appropriate types and levels of conservation programs within the region were not available. HRCP was designed, in part, to fill this information gap.

The project has other historical roots as well as the 1980 law. In particular, the Natural Resources Defense Council (NRDC) had debated with the region's utilities (including BPA) the relative advantages and disadvantages of aggressive utility conservation programs. NRDC saw such programs as viable and attractive alternatives to construction of conventional coal and nuclear power plants. The utilities, on the other hand, were unsure about the costs of purchasing conservation resources and the amount of these resources they could obtain. That is, the utilities felt that studies showing the enormous technical potential for improved energy efficiency failed to consider the difficulties and costs associated with realizing that potential. HRCP was intended to find out how much conservation could be purchased, at what cost, and how quickly.

Several residential retrofit programs have operated in the Pacific Northwest during the past few years. Although evaluations of these programs provide useful information (Burnett 1982; Hannigan and King 1982; Hirst et al. 1985; McCutcheon 1983; and Weiss 1982), they give little insight concerning the maximum limits of such programs.

HRCP is funded by BPA and implemented by PP&L in cooperation with the Hood River Electric Cooperative (HREC). Several advisory groups helped design the project and continued to provide guidance as the project was implemented. These groups include representatives from the local community, NRDC, the Council, the region's electric utilities (represented by the Pacific Northwest Utilities Conference Committee and the Northwest Public Power Association), BPA, PP&L, HREC, and others.

A comprehensive set of measures was included in HRCP (Table 1) to test the reasonable limits of a residential retrofit program. The cost-effectiveness limit for HRCP is based on an assumed 35-year life for the measures and the marginal cost of a new coal-fired power plant (see Table 2 of Hirst and Goeltz 1985). Although the method of calculating the retrofit measure cost-effectiveness limit was different from that used by the Council (1983), the result is essentially the same ($1.15/kWh vs $1.12/kWh in the regional plan).

Table 1. HRCP conservation measures

Measure	Target level
Home energy audit	All electrically heated homes[a]
Ceiling insulation and appropriate ventilation	R-49
Floor insulation[b]	R-38
Wall insulation	R-11 to R-19
Cold and hot water pipe insulation to water heater[c]	R-3
Dehumidifiers and air-to-air heat exchangers[d]	As required
Clock thermostats	Where applicable
Duct insulation	Crawl space R-11, attic R-30, where applicable
Storm windows and thermal replacement sash and glazing	Triple-glazing
Thermal doors and double-glazed sliding doors	Where applicable
Caulking and weatherstripping	Where applicable
Outlet and switchplate gaskets[c]	Where applicable
Heat pump conversion of existing furnace system[d]	Where appropriate conventional measures cannot be installed
Electric water heater wraps[c]	R-11
Low-flow showerheads and other hot water flow regulators[c]	As required

[a]Audits were provided to homes heated with nonelectric fuels, primarily to maintain good relations with the community.

[b]Includes insulation of hot and cold water pipes, if under the floor.

[c]These four low-cost measures are installed by the auditor, at the time of the energy audit or soon thereafter.

[d]These measures are installed only in special circumstances.

Source: Peach et al. (1984).

The town and county of Hood River, Oregon (plus the town of Mosier in Wasco County) were selected as the location 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 (HREC) and private (PP&L) utilities; 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 almost 50 miles east of Portland and is bounded on the north by the Columbia River (Fig. 1). Additional information on Hood River and the reasons for its selection are in Appendix A of PP&L (1983) and French et al. (1985).

The contract between BPA and PP&L to initiate this $21 million demonstration was signed in May 1983. Energy audits were started in Fall 1983, and installation of retrofit measures began in January 1984 (Fig. 2). All households in the area were eligible for energy audits. However, the project pays for retrofit measures only in homes with permanently installed (before March 1983) electric space heating equipment. This eligibility requirement is based on the notion that the program is intended to purchase "conservation electricity resources." Between October 1983 and December 1985 (when the field work was completed), 3249 eligible households contacted HRCP, of whom 3189 received energy audits and 2988 had major measures installed in their homes (Hirst and Goeltz 1986). [See Philips et al. (1986), French and Peach (1986), and Quinn and Oliver (1985) for discussion of implementation issues.] Roughly 250 additional eligible homes did not participate in HRCP.

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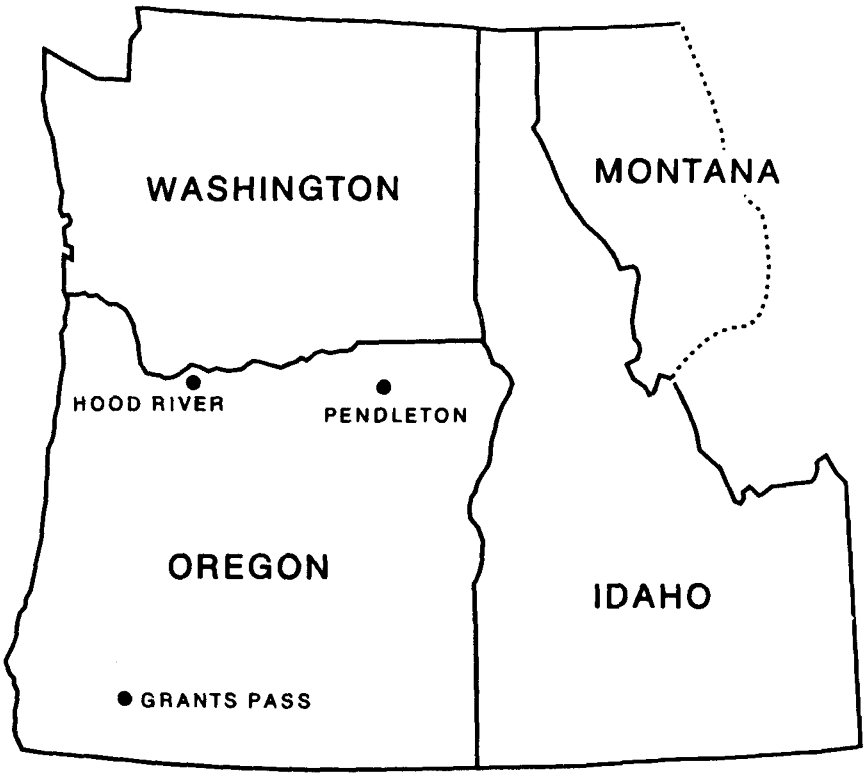

Fig. 1. Map of the Pacific Northwest region showing the location of Hood River and the two comparison communities (Pendleton and Grants Pass). Data from the comparison communities will be used in the analysis of HRCP-induced electricity savings.

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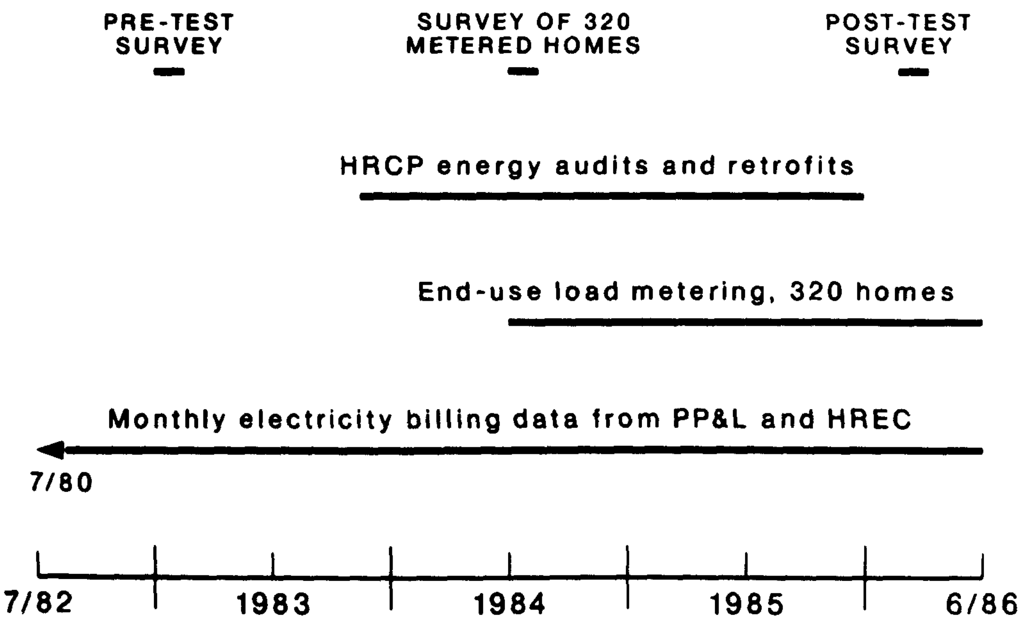

Fig. 2. Timeline of the Hood River Conservation Project.

HRCP EVALUATION DATA BASE

Because HRCP is a major and complex project, the data associated with the project are correspondingly extensive and detailed. More important, the project's focus on research required collection of extensive data (see Table 3 in Hirst and Goeltz 1985; Oliver, Peach and Modera 1984; and PP&L 1982).

The data available from HRCP include pre- and post-program mail surveys conducted among random samples of households in Hood River and the two comparison communities [in early 1983 (Berg and Bodenroeder 1983) and Spring 1986, respectively], monthly electricity billing data from 1980 through mid-1986 for all households in the three communities, detailed end-use load and weather data (15-minute intervals) and onsite home interviews for about 300 HRCP participant homes, a wood use survey conducted in Spring 1986 among HRCP participants, and a nonparticipant survey conducted in late 1985 among the few eligible households that did not participate.

The field-office data base provides the richest information on participants. These data include household demographics and appliance holdings at the time of the energy audit. The audit analyzed the applicable retrofit measures and their likely energy savings. The auditors installed several low-cost water-heating-conservation and infiltration-reduction measures at the time of the audit (or soon thereafter), and these actions were also recorded.*

---

*The audit procedure did not estimate electricity savings for the four auditor-installed measures. Our estimates of the savings for these measures, based on conversations with staff at PP&L, BPA, and other research organizations (Meier 1985 and Biemer, Auberg, and Ek 1985) are: 350 kWh/year for water heater wrap, 350 kWh/year for low-flow showerheads, 400 kWh/year for a set of outlet gaskets, and 30 kWh/year for hot water pipe wrap. Anderson (1986) estimated the energy <u>penalty</u> of the air-to-air heat exchanger at 510 kWh/year for each unit.

Barriers that prevented recommendation or installation of retrofit measures were identified. A "barriers" form (Fig. 3) was completed at every stage in the project process (during the energy audit, between audit and contractor bid, during contractor bid, during retrofit installation, and during postinstallation inspection) to capture all the reasons for partial intallation or noninstallation of measures. The field-office data base, especially the barriers form, provides the raw material for the analyses presented here.

HRCP #104
Rev. 3/84

Customer Name:
Customer Acct. #:

BARRIERS

Measures		Barrier #	Other Barriers
Ceiling Insulation/Attic Vent	1.		
Floor Insulation/Gr. Cover/Pipe Wrap	2.		
Wall Insulation/Kneewalls	3.		
Duct Insulation	4.		
Windows	5.		
Sliding Glass Doors	6.		
Insulated Doors	7.		
Window & Door Frame Caulking	8.		
Weatherstrip Windows/Sliding Doors.	9.		
Weatherstrip Doors.	10.		
Clock Thermostat.	11.		
Air to Air Heat Exchanger	12.		
Water Heater Wrap	13.		
Water Heater Pipe Wrap.	14.		
Low Flow Shower Heads	15.		
Infiltration Gaskets	16.		
Dehumidifier.	17.		
Heat Pump Conversion	18.		

Point of Barrier Occurrence (check one)

- ☐ Prior to EA
- ☐ During EA
- ☐ Between EA and Bid
- ☐ While Contractor Bidding Job
- ☐ After Customer Agreement
- ☐ During Installation
- ☐ During Inspection

Refused

☐ Audit ________ Barrier #

or

☐ Weatherization ________ Barrier #

________ Prepared by ________ Date

________ Auditor ID#

BARRIER NUMBERS

Customer Barriers
1 - Degrade Appearance
2 - Make House Too Tight
3 - Refuses Contact with Utility
4 - Non-Electric Space Heat
5 - House Already Weatherized
6 - Measure Already Installed
7 - Customer Will Pay In Long Run
8 - Refuses Handouts
9 - Dislikes Grade of Materials
10 - Violates Privacy
11 - Contractors Not Acceptable
12 - House Vacant
13 - Owner Unavailable
14 - No Reason Given
15 - Interfere With Use Of Area/Appliance
16 - Not Cost Effective

Other Barriers
99 - Other (provide detail)

Reason For Supplemental Payment
40 - Exceeds Product or Installation Standards
41 - Exceeds Cost Effective Limit
42 - Exceeds Program Level
43 - Exception for Monitored Home

Physical Barriers
60 - Limited Physical Access
61 - Unable to Vent
62 - Ceiling will not Support Load
63 - Existing Insulation/Installation
64 - Ground Water Problem
65 - Rodent/Animal Problem
66 - Non Compatible Structure (e.g. Slab)
67 - Existing Dry Rot/Termite
68 - Structural Limitation
69 - Non Compatible With Heating Equipment
70 - Water Heater not Electric
71 - Audit Contract Restriction

Fig. 3. HRCP form used to record barriers to recommendation or installation of retrofit measures.

3. SUMMARY STATISTICS ON PARTICIPANT HOMES

HOMES WITH NO MAJOR MEASURES INSTALLED

Almost all (92%) of the households that contacted HRCP had at least one major measure installed in their homes by the Project.* Only 8% (261 of 3249) had no major retrofit measures installed. A few of the four low-cost measures installed by the auditors (outlet gaskets, water heater wrap, hot water pipe wrap, and low-flow showerhead) were installed in these homes. On average, 1.9 measures/home were installed in these homes, compared with 7.4 measures in the other 92% of the homes.

The homes with no major measures installed differed substantially from the other homes (Table 2). The homes with no major measures are characterized by households with higher incomes, more education, that have lived in their homes for fewer years. In addition, these households are more likely to own their homes, to live in single-family homes that are newer and larger, and to have more electricity-using equipment than the other households. (These differences are generally significant at the 1% level or better.)

Many of the households in homes with no major measures installed had installed retrofit measures earlier, either on their own or with assistance from prior PP&L or HREC conservation programs. For example, 25% of these 261 households had participated in a prior conservation program, compared with 8% of the other households. Thus, participation

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*Major retrofits include the four insulation, three window and door, three infiltration reduction, and clock thermostat measures (measures 1 - 11, Fig. 3).

in a prior program is strongly related to the potential for energy savings in HRCP.*

Table 2. Comparison of HRCP homes with major measures installed vs those with no major measures installed[a]

	HRCP participants, with or without major measures installed	
	Without measures	With measures
Household income ($)[b]	24,600	21,000
Years in present home[b]	6.4	8.4
Number of household members	2.7	2.7
Education of household head (years)	13.0	12.7
Tenure (% that own home)[b]	78	66
Year house built[b]	1968	1958
House floor area (ft^2)	1340	1260
Single-family (% of homes)[b]	75	61
Presence of electric equipment (%)		
Air conditioner(s)	26	20
Clothes washer[b]	88	76
Dishwasher	64	58
Electric clothes dryer[b]	86	74
Food freezer	60	57
Number of households	261[a]	2988

[a]Data were available for only 201 of these homes; energy audits were not conducted in the other 60 homes.

[b]These differences are statistically significant at the 1% level.

*Participants in previous programs generally had fewer HRCP-installed retrofits than those who did not participate in prior programs. The mean cost of HRCP retrofits was $3400 for participants in prior programs, compared with $3900 for the other HRCP participants. Comparison of retrofit costs is obscured by large differences in housing type between those who did and did not participate in prior programs. Almost 95% of the previous participants live in single-family homes, compared with 58% of the remaining HRCP participants. Considering single-family homes only, the mean cost of HRCP retrofits was $3500 for prior participants, compared with $5500 for the other HRCP participants.

Barriers to installation of all major measures arose for various reasons. Overall, lack of cost-effectiveness (failure to meet the $1.15/kWh criterion) was the most frequent barrier (Table 3). This single barrier, generally identified by the HRCP office staff after receipt of the contractor bid, accounted for 56% of these 261 homes.* In 23% of these cases, the audit could not be conducted because the residents refused to allow the auditor to enter the house, the house was vacant, or the occupants were unavailable. Finally, 21% of these households declined to participate in HRCP after the energy audit was conducted. Thus, residents changed their minds about participation in HRCP some time after their initial contact with the Project in almost half (44%) of these cases.

Table 3. Reasons for noninstallation of any major retrofit measures

	Percentage of homes with no major measures installed[a]
No energy audit conducted	
Various customer barriers	23
Audit conducted, no major measures installed[b]	
Not cost-effective	56
Other	21

[a]Based on 261 homes.

[b]Most (72%) of these barriers were identified by the HRCP office staff during their calculations of measure cost-effectiveness; 23% were identified between the audit and bid.

*Lack of cost-effectiveness was cited for almost 90% of the 66 homes that had participated in a prior program.

AGGREGATE POTENTIAL

The present analysis includes 15 measures (1 - 11 and 13 - 16 in Fig. 3).* The hypothetical potential existed to install 48,735 measures (15 measures in 3249 homes).** Slightly less than half were actually installed by the program (Table 4), and measures were neither recommended nor installed in nearly half the cases. Thus most noninstallations occurred because the measure was not recommended.

Assume for the moment that all measures could be installed in all homes (a maximum definition of potential savings). If the average estimated savings for each measure were equal to the average savings for the homes in which the measure was actually installed, the potential savings would be 12,500 kWh/house.† The estimate of savings produced by measures actually installed is, of course, much less. The estimated savings for the auditor-installed measures in the homes with no major measures installed average 610 kWh/house. The estimated savings, averaged over all 15 measures, for measures installed in the remaining homes is 6,140 kWh. Thus, the average estimated savings per eligible

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*Heat pumps, dehumidifiers, and AAHXs are excluded from this analysis. The first two measures were almost never installed by HRCP. AAHXs are not intended to save energy; they were installed only if indoor air pollutants were a problem (BPA 1984). An average of 1.1 AAHX were installed in 801 homes at an average cost of $1270, and had an estimated energy penalty of 560 kWh/year (which includes the electricity to operate the blower and the electricity required to compensate for the energy content of the exhaust air).

**One could define the potential even more expansively to include measures not installed in the roughly 250 eligible homes that had no contact with HRCP.

†These are engineering estimates. Reliable data on actual electricity savings will not be available until mid-1986 (after a full postretrofit heating year, 1985/86.)

Table 4. Distribution of HRCP measures by recommendation and installation[a]

	Percent of total measures
Homes with no major measures installed (8%)[b]	8
Remaining homes (92%)	
Measures not recommended, not installed	38
Measures recommended	
Not installed	9
Installed	45

[a]Based on 48,735 measures (3249 homes and 15 measures).

[b]Because a few measures were installed by the auditor in these homes, the 8% could be reduced to 7% and the 45% (recommended/installed) could be increased to 46%.

house for measures actually installed is 5,700 kWh, almost half the theoretical potential (top part of Table 5).

The preceding discussion is based on an artificial and unrealistic definition of potential (installation of every measure in every home). If one assumes that program planners have accurate information on the current condition of homes in their service area, then the potential can be defined to include only those measures applicable to the housing stock in that area. This defines potential on the basis of the measures recommended during the energy audit. Of the 26,354 measures recommended during energy audits of the 2988 homes that had major measures installed, 83% were actually installed. However, these installed measures accounted for 93% of the potential electricity savings for the measures recommended during the audits (bottom part of Table 5).

Thus, the fraciton of potential saving achieved by a program depends on how potential is defined. Based on a hypothetical ideal of installing all measures in all homes, HRCP achieved 46% of its potential. Based on the auditor recommendations, HRCP achieved 93% of its potential.

Table 5. Comparison of maximum potential electricity savings with estimates of savings due to measures installed by HRCP[a]

	Audit estimate of savings per house (kWh/year)
All homes	
Homes with no major measures installed 0.08*610 kWh/house	50
Remaining homes 0.92*6140 kWh/house	5,650
Total	5,700
Total potential savings, if all measures installed in all homes	12,500
Homes with major measures installed	
Measures installed in homes with major measures	6,140
Total potential savings, if all audit recommendations installed	6,590

[a]Based on 3249 homes and 15 measures.

ESTIMATED SAVINGS AND COSTS FOR RETROFIT HOMES

The remainder of this section involves only the 2988 homes in which at least one major retrofit measure was installed. The HRCP retrofit measures (Fig. 3) were grouped into five categories:

Insulation - ceiling, walls, floor, heating ducts;

Windows and doors - storm windows, sliding glass doors, thermal doors;

Infiltration - caulking, window weatherstripping, door weatherstripping, outlet gaskets;

Water heating - water heater wrap, hot water pipe wrap, low-flow showerheads;

Other - clock thermostat, dehumidifier, air-to-air heat exchanger, heat pump.

The energy audits identified an average potential electricity savings of 6590 kWh/year (Table 6). The estimated savings for measures installed by HRCP averaged 6140 kWh. Even though 17% of the recommended measures were not installed, only 7% of the estimated potential savings was not achieved.

Table 6. Retrofit measures recommended and installed by HRCP

Measure type[a]	Mean value, per house		
	Estimated savings (kWh)[b]		Actual installed cost ($)
	Audit	Installed	
Insulation	3930	3480	1790
Windows and doors	1550	1640	1760
Infiltration	550	480	150
Water heating	480	480	20
Clock thermostat	80	60	40
Total	6590	6140	3760

[a]Insulation measures include ceiling, wall, floor, and heating duct insulation. Window and door measures include storm windows, thermal doors, and sliding glass doors. Infiltration measures include caulking, window weatherstripping, door weatherstripping, and outlet gaskets. Water heating measures include water heater insulation, water heater pipe insulation, and low-flow showerheads.

[b]The first column is the savings estimated at the time of the energy audit. The second column is the savings estimated by the auditor after contractor installation of measures. More or less of the measure was often installed than was recommended in the initial audit.

The average cost of installed measures was $3760 (Table 6 and Fig. 4). Only 10% of the participants paid anything for the HRCP retrofit measures installed in their homes. These households paid for measures that exceeded HRCP levels (e.g., attic insulation beyond R-49), exceeded the HRCP cost-effectiveness limit (i.e., cost more than $1.15/kWh-saved) or exceeded HRCP standards (e.g., storm windows that cost more than those called for by HRCP specifications). These households paid an average of $430. Averaged over all these homes, households paid only 1% of the total retrofit cost.

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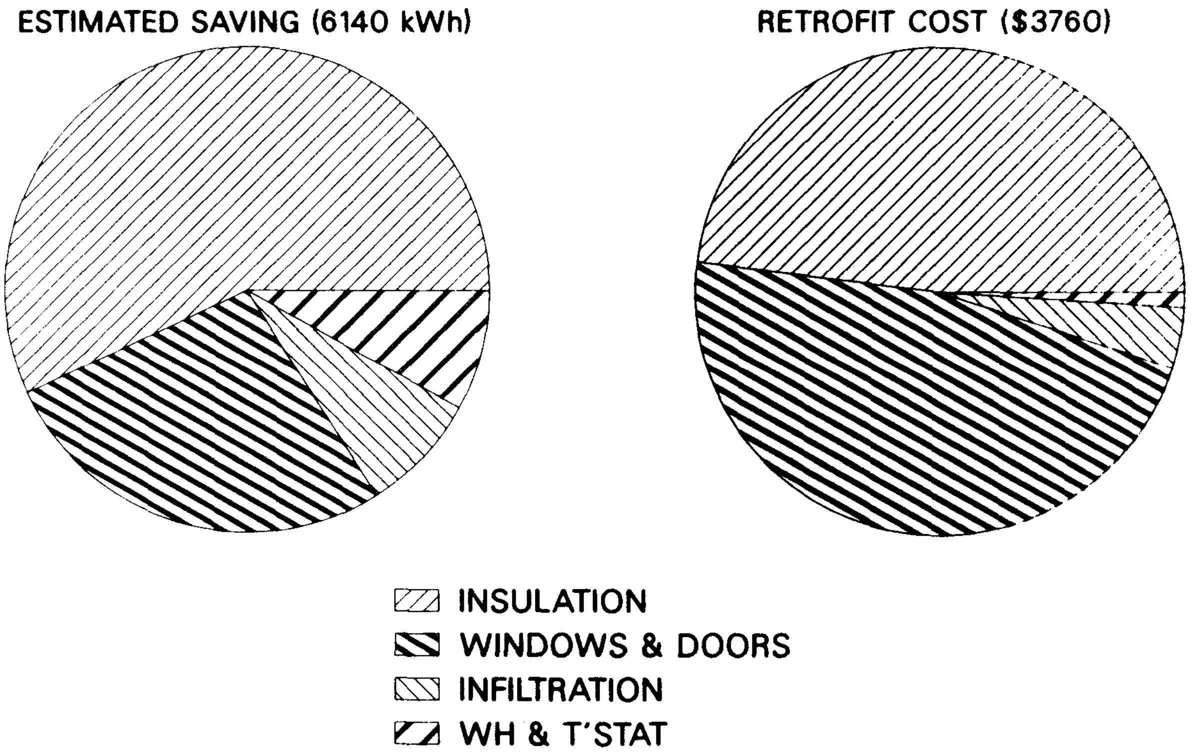

Fig. 4. Estimated electricity savings and retrofit costs for HRCP-installed measures. (WH & T'STAT refers to water heating measures and clock thermostats.)

The HRCP payment for retrofit measures, averaged over these homes, was 69¢/kWh-saved, far below the cost-effectiveness limit (Fig. 5).*

The insulation measures as a group dominate the estimated energy savings for the installed measures (Table 6 and Fig. 4), accounting for 57% of the total savings and 48% of the total cost. The difference in percentages of savings and cost suggest that these measures are relatively cost-effective. The window and door measures, on the other hand, are expensive, accounting for only 27% of the estimated electricity savings but 47% of the total retrofit cost. The infiltration reduction, water heating, and clock thermostat measures account for small fractions of both cost and savings.

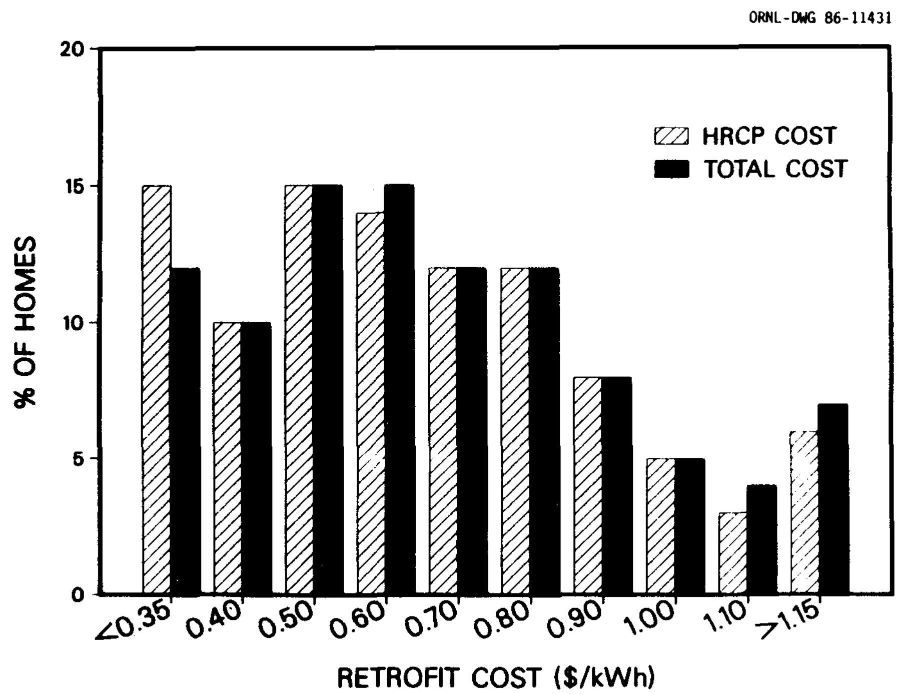

Fig. 5. Distribution across homes of HRCP payments and total costs for retrofit measures ($/estimated first-year kWh-saved).

*These totals include AAHX installations. Excluding the cost and energy penalty of AAHX reduces the total cost of HRCP retrofit measures to 61¢/kWh.

The relationship between total retrofit cost and preretrofit (1982/83) weather-normalized annual electricity use is surprisingly weak; the correlation coefficient (r) between these two variables is only 0.30 (Fig. 6). We had expected preretrofit electricity use to be a strong predictor of the need for retrofit measures and therefore of actual retrofit cost.

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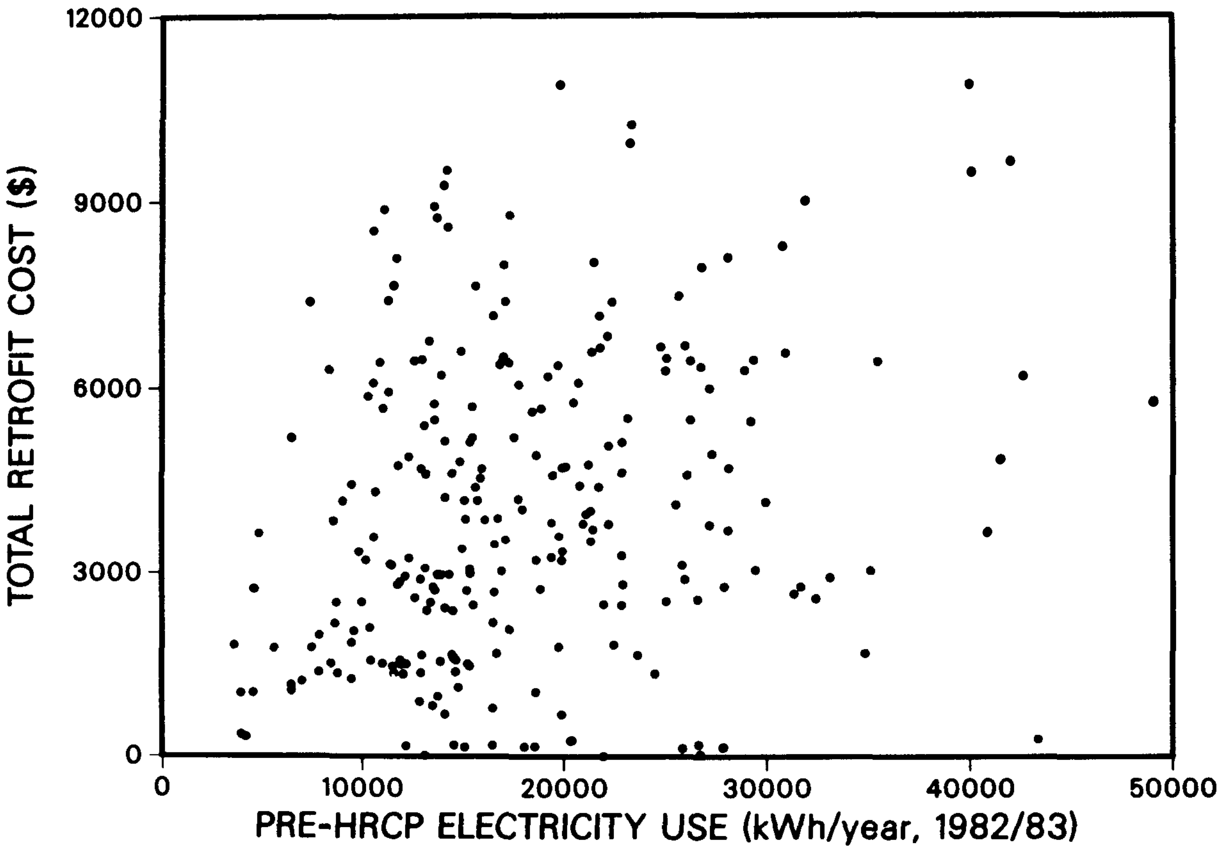

Fig. 6. Actual retrofit cost as a function of 1982/83 weather-adjusted electricity use for homes that participated in HRCP and received at least one major retrofit measure. (To improve clarity, the figure shows data for only a 1/10 random sample of these homes.)

SAVINGS AND COSTS BY HOUSE TYPE AND AGE

The preceding discussion presented summary statistics for the 2988 homes retrofit by HRCP. Here we examine these statistics by housing type (Table 7) and by age of housing unit (Table 8).

Single-family homes account for the majority (60%) of HRCP participants. Because these dwelling units are, on average, substantially larger than multifamily units and mobile homes, the energy savings associated with recommended and installed measures and the retrofit costs are much higher for single-family homes. The ratios of estimated energy savings (installed/recommended measures) are much higher for single- and

Table 7. Estimated electricity savings and retrofit costs for measures recommended and installed by HRCP, by housing type

	Mean values, by housing type[a]		
	Single-family	Multi-family	Mobile home
Estimated savings (kWh/yr)			
Recommended measures	8150	3780	4160
Installed measures	7680	3760	3230
Installed savings, as percent of recommended savings (%)[b]	94	104	78
Retrofit cost ($)	5380	2180	2370
Cost per first-year estimated savings (¢/kWh)[b]	79	60	78
Year house built	1952	1962	1973
House floor area (ft^2)	1530	780	1060
Number of household members	2.9	1.9	2.6
Number of homes	1811	513	534

[a]Multifamily includes all structures with two or more dwelling units. Mobile homes include trailers. Of the 2988 homes, 140 cabins are not shown in this table.

[b]These represent the mean values of the ratios, not the ratios of the mean values.

Table 8. Estimated electricity savings and retrofit costs for measures recommended and installed by HRCP, by year house was built

	Mean values, by year house built					
	≤1945	1946-1959	1960-1969	1970-1974	1975-1979	1980+
Estimated savings (kWh/yr)						
Recommended measures	9720	7900	5800	4900	4370	3620
Installed measures	9130	7460	5490	4540	3860	3210
Installed saving, as percent of recommended saving (%)	96	97	94	92	88	96
Retrofit cost ($)	5500	5180	4310	3330	2990	2110
Cost per first-year estimated saving (¢/kWh)	66	75	85	73	72	60
Number of homes[a]	782	341	454	600	598	209

[a]Year built was missing for four of the 2988 homes.

multi-family units than for mobile homes. About 8%, 1%, and 6% of the single-family, multifamily, and mobile home units, respectively, had no major measures installed.

Finally, the estimated electricity savings per unit floor area are about 50% higher for single- and multi-family units than for mobile homes. Apparently, the opportunities to retrofit mobile homes are limited.

There are also substantial differences in estimated savings and costs as a function of house age (Table 8). As expected, the savings and retrofit costs increase with house age. This is reflected in the incidence of cases with no major measures installed: only 3% of the homes constructed before 1960 had no major measures installed, compared with 7% for homes constructed during the 1970s and 17% for homes constructed during the 1980s. However, the cost-effectiveness of retrofit is largely independent of house age.

4. INDIVIDUAL RETROFIT MEASURES: INSTALLATION AND BARRIERS

The preceding section reviewed HRCP's overall success in installing retrofit measures in participant homes. This section focuses on individual measures recommended and installed in the 2988 homes that had at least one major retrofit measure installed.

RECOMMENDATION AND INSTALLATION

Several measures were recommended in the vast majority of homes (Table 9): ceiling insulation, floor insulation, storm windows, caulking, and door weatherstripping (Figs. 7 - 10). Heating duct insulation, insulated doors, and window weatherstripping were installed in very few homes. Homes with baseboard heating have no heating ducts, insulated doors are rarely cost-effective, and the need for window weatherstripping was usually obviated by installation of storm windows.

The measures also differ substantially in retrofit cost and in estimated energy savings. Storm windows and floor insulation are the most expensive measures; the four measures installed at the time of the audit are the least expensive. Estimated energy savings are largest for wall insulation, which had a relatively low retrofit cost. Ceiling and floor insulation and storm windows are also large energy savers.

BARRIERS FOR MEASURES NOT INSTALLED

The obstacles to recommendation and/or installation of retrofit measures noted in the HRCP barriers form (Fig. 3) do not constitute an exhaustive and mutually exclusive set of choices. For example, the presence of R-30 insulation in the attic of a home could lead to any one of three barriers:

Measure Already Installed,
Not Cost Effective,
Existing Insulation/Installation.

The first barrier occurred if the resident knew how much insulation was in the attic and did not allow the auditor to inspect the attic. The second occurred if the auditor computed the estimated electricity savings for addition of R-19 to bring the ceiling to the HRCP level of

Table 9. Retrofit measures recommended and installed by HRCP[a]

Measure	Percentage of homes in which measure			Installed		Ratio of cost to estimated savings[c] (¢/kWh)
	Recom-mended	Installed	Installed as % of recommended	Cost ($)	Savings (kWh/yr)[b]	
Insulation						
Ceiling	88	67	76	960	1690	57
Floor	87	63	72	1350	2080	65
Wall	49	39	80	720	2460	29
Duct	19	12	63	270	720	37
Windows and doors						
Storm windows	99	89	90	1730	1670	104
Sliding glass doors	40	29	73	720	500	143
Insulated doors	12	3	25	430	210	208
Infiltration						
Caulking	89	78	88	110	140	82
Window w'strip	17	0	0	-	-	-
Door w'strip	90	69	77	80	50	180
Outlet gaskets	d	85	100	10	400	3
Clock thermostat	32	26	81	150	250	59
Water heater						
Insulation	d	51	100	20	360	6
Pipe insulation	d	63	100	10	30	18
Low-flow showerheads	d	62	100	10	450	2

[a]Based on 2988 homes.

[b]These are engineering estimates of expected electricity savings for the measures installed by HRCP.

[c]These numbers are the ratios of the mean cost to mean estimated annual savings for each measure.

[d]Installations equal recommendations for these four auditor-installed measures.

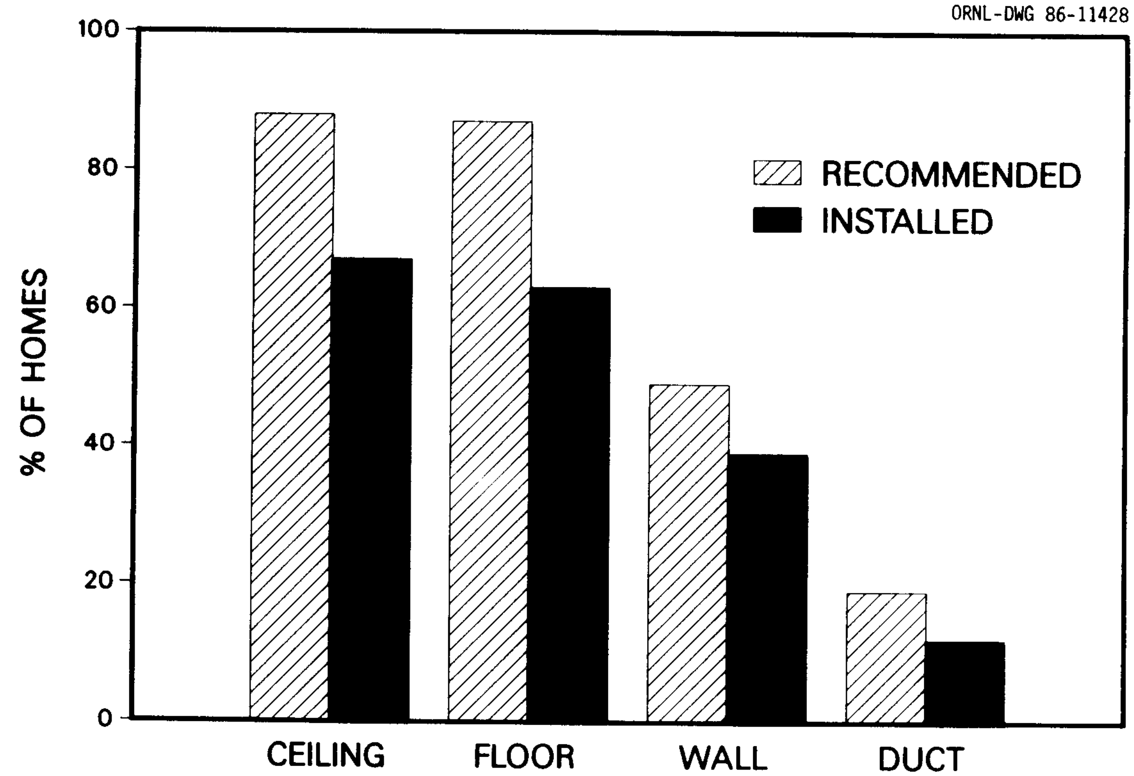

Fig. 7. Percentage of HRCP homes in which insulation measures were recommended and installed.

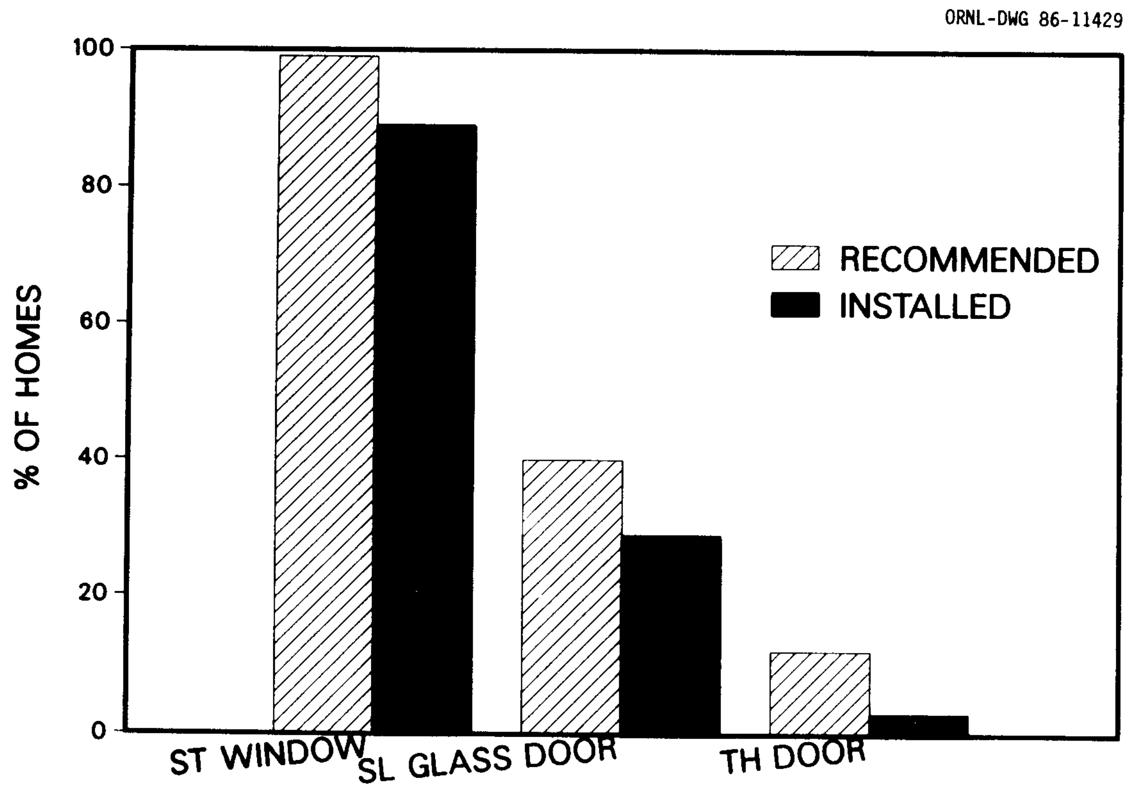

Fig. 8. Percentage of HRCP homes in which window and door measures were recommended and installed.

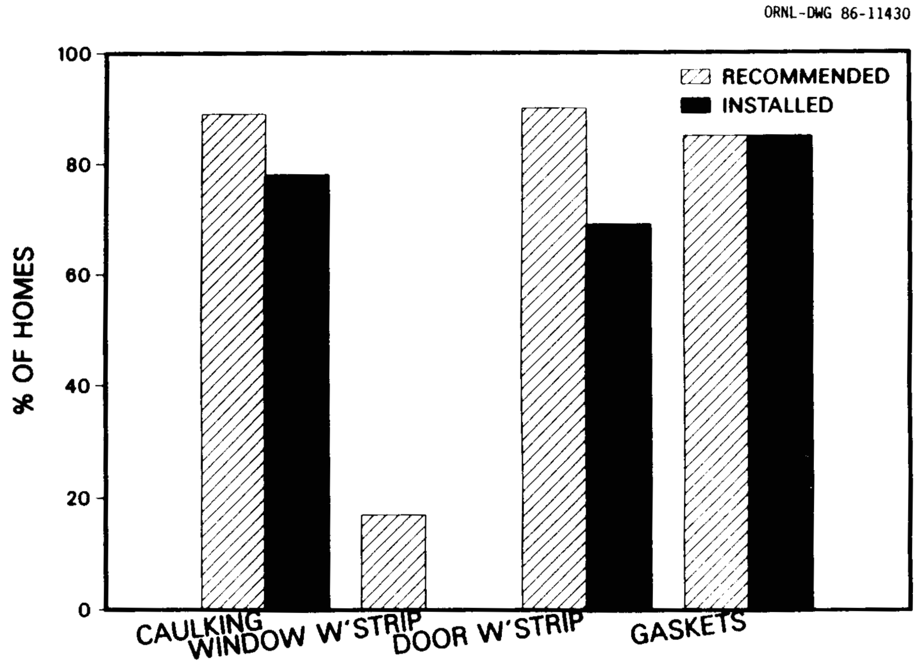

Fig. 9. Percentage of HRCP homes in which infiltration measures were recommended and installed. Window weatherstripping was rarely installed because installation of new windows and frames obviates the need for weatherstripping. Outlet gaskets were installed at the time of the energy audit so recommendations equal installations.

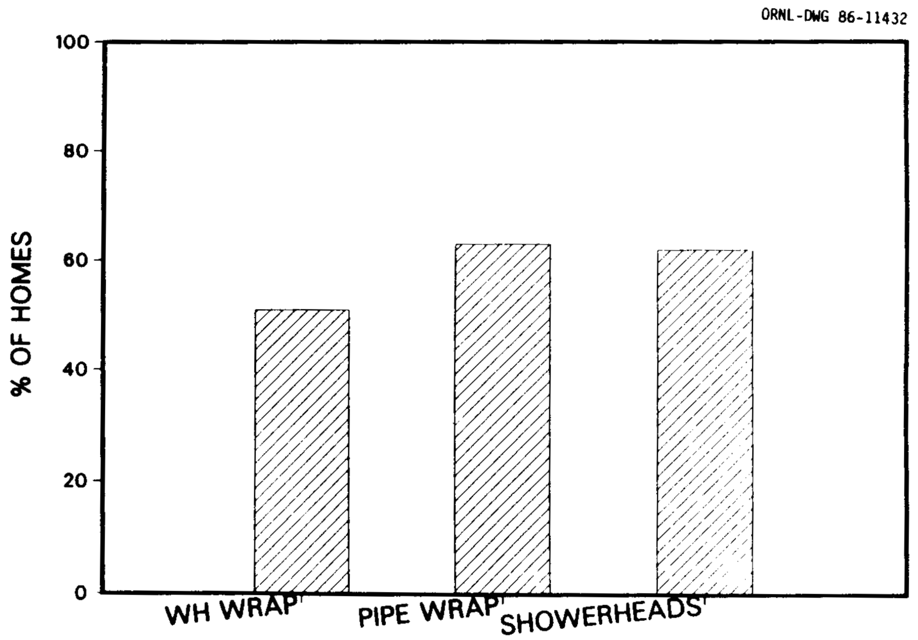

Fig. 10. Percentage of homes in which water heating measures were installed (identical to percentages in which measures were recommended).

R-49; staff in the HRCP office then determined, after the contractor prepared a bid, that the installation cost was too high to pay for the estimated savings, given the $1.15 limit. The third choice occurred during the audit if the auditor recognized that the attic already contained sufficient insulation.

We aggregated the individual barriers into five groups:

> Not compatible (66, 69, 70*) - refers to measures that are not applicable to the particular house, such as duct insulation in a house that has no ducts or floor insulation for a house on a concrete slab.
>
> Physical (60-62, 64, 65, 67, 68, 71) - refers to conditions in the house that prevent installation of a measure, such as spaces too small to install additional insulation or water heaters without pressure relief valves.
>
> Existing installation (16, 63) - refers to situations in which some or all of the recommended measure is already in place; installation of more of the measure would not be cost-justified.
>
> Customer (1-15) - refers to cases in which the resident decides that the measure will not be installed.
>
> Other/none (40-43, 45, 99) - refers to other barriers that are infrequently cited or to measures not installed for which no barrier was recorded.

Noncompatible conditions were cited for 19% of the noninstalled measures (Table 10 and Fig. 11).** An additional 31% of the measures were not installed because of physical conditions that prevented installation. Thus, half of the measures could not be installed, regardless of potential energy savings or measure costs.

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*These numbers refer to the barriers in the form shown in Fig. 3.

**More than one barrier was sometimes identified for individual measures. On average, there were 1.2 barriers per noninstalled measure. In addition, barriers were not recorded for 3% of the noninstalled measures. The discussion, Tables 10 and 11, and Figs. 11 and 12 ignore these small anomalies.

Table 10. Barrier type for measures not installed by HRCP[a]

Measure	Percentage of barriers by barrier type[b]: Existing Installation	Physical	Not Compatible	Customer	No. of measures not installed
Insulation					
Ceiling	32	62	2	2	1919
Floor	35	55	5	2	2058
Wall	74	20	3	2	2455
Duct	14	17	68	0	2951
Windows and doors					
Storm windows	84	3	0	7	350
Sliding glass doors	18	43	35	3	2256
Insulated doors	93	2	0	1	3170
Infiltration					
Caulking	61	32	0	4	815
Window w'strip	94	4	0	1	3163
Door w'strip	74	20	0	3	1010
Outlet gaskets	12	68	1	13	470
Clock thermostat	1	1	94	2	2254
Water heater					
Insulation	24	59	1	15	1926
Pipe insulation	11	75	1	11	1354
Low-flow showerheads	16	71	1	8	1313
Averages	45	31	19	4	27,464

[a]Based on 2988 homes and 15 measures.

[b]Percentages do not add to 100% because other barriers occasionally occurred, accounting for 2% of the total.

The presence of partial measures or lack of cost-effectiveness (NCE) prevented installation in another 45% of the cases. In these cases, the homes already had sufficient quantities of a measure (e.g., double-pane windows) so additions to bring the measure up to the project level (e.g., triple-pane) could not be justified.

Customer concerns prevented installation of only 4% of the measures. Lack of customer barriers is surely caused largely by the fact that almost all measures were installed at no cost to the household. Finally, other barriers were cited for less than 2% of the measures.

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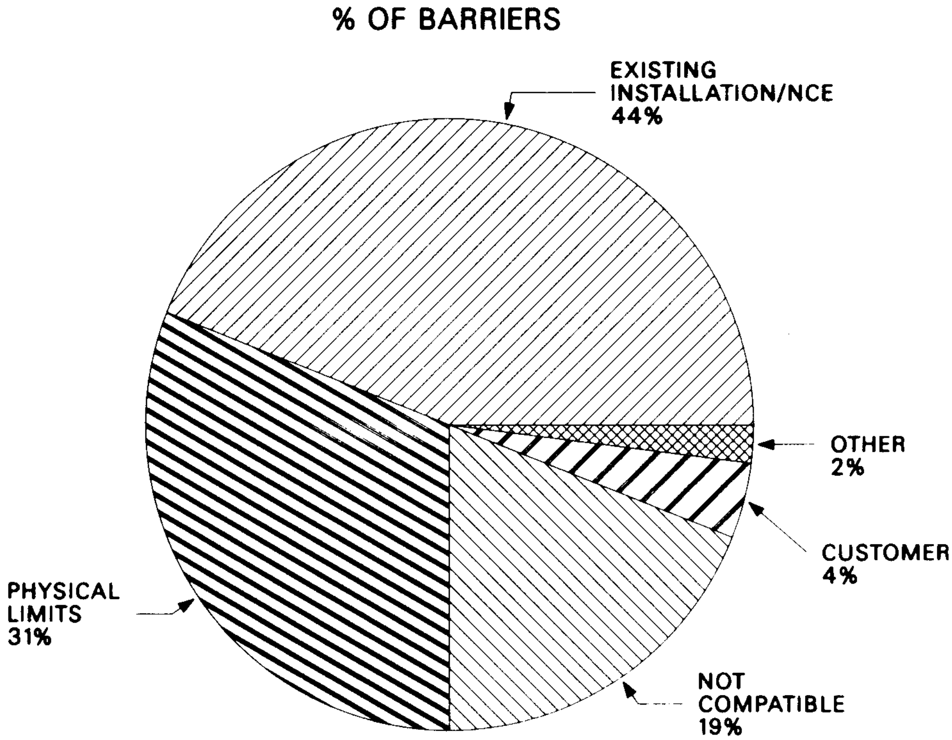

Fig. 11. Distribution of barriers for measures not installed, by type of barrier. (NCE is not cost-effective.)

The vast majority of barriers (81%) were identified during the energy audit (Table 11 and Fig. 12). The only exceptions were ceiling and floor insulation and caulking (for which some barriers surfaced during the contractor bid) and storm windows (for which more barriers appeared during the bid process than during the audit). This result suggests that the auditors generally did a good job examining the suitability of each measure for each house.

The auditors were particularly adept at identifying barriers related to incompatibility with the heating system or structure and physical limitations. Barriers related to cost-effectiveness and customer concerns were frequently identified during the contractor bid phase (which included calculations of cost-effectiveness by the HRCP office staff).

Table 11. Point of barrier occurrence for measures not installed[a]

Measure	Percentage of barriers by point of barrier			
	Audit	Between audit/bid	During bid	After bid
Insulation				
Ceiling	70	4	21	6
Floor	65	3	24	8
Wall	84	2	9	5
Duct	88	1	7	4
Windows and doors				
Storm windows	10	17	62	10
Sliding glass doors	80	3	14	3
Insulated doors	91	1	5	4
Infiltration				
Caulking	40	7	38	15
Window w'strip	90	2	5	3
Door w'strip	30	6	36	28
Outlet gaskets	95	3	0	2
Clock thermostat	91	0	3	5
Water heater				
Insulation	94	4	0	2
Pipe insulation	92	5	0	2
Low flow showerheads	93	4	0	2
Averages	81	3	11	5

[a]Based on 2988 homes.

Only a few of the 32 barriers included in the HRCP form (Fig. 3) were frequently cited (Table 12). Structural limitation was the predominant barrier for several measures: ceiling and floor insulation, sliding glass doors, and low-flow showerheads.

Existing installation (presence of the measure), the most frequently cited barrier, was cited for the majority of homes in which wall insulation and weatherstripping were not installed. Existing installation was also a major barrier for caulking.

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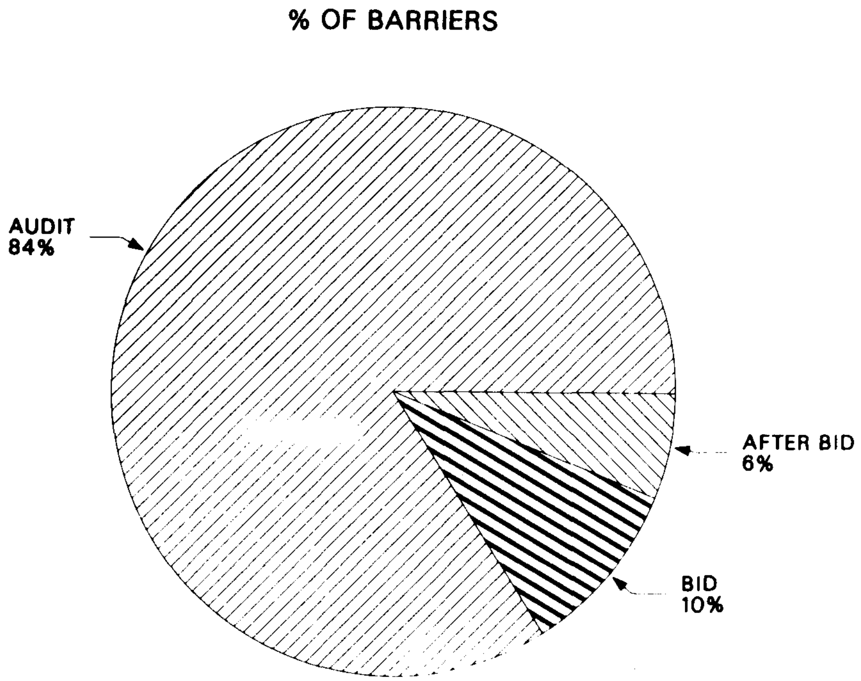

Fig. 12. Distribution of barriers by time of identification.

Table 12. Most frequently cited individual barriers[a]

	Percentage of barriers					
	Structural limitation	Existing installation	Noncompatible structure or heating equip.	Not cost-effective	Limited access	Restriction in auditor contract[b]
Insulation						
Ceiling	34	-	-	21	26	-
Floor	30	-	-	26	21	-
Wall	-	66	-	-	-	-
Duct	-	-	68	-	-	-
Windows and doors						
Storm windows	-	-	-	81	-	-
Sliding glass doors	43	-	35	-	-	-
Insulated doors	-	20	-	75	-	-
Infiltration						
Caulking	32	38	-	24	-	-
Window w'strip	-	50	-	44	-	-
Door w'strip	20	50	-	24	-	-
Outlet gaskets	-	-	-	-	-	60
Clock thermostat	-	-	94	-	-	-
Water heater						
Insulation	24	24	-	-	-	20
Pipe insulation	30	-	-	-	-	27
Low-flow showerheads	44	-	-	-	-	27
Total[c]	19	23	15	22	6	5

[a]The percentages are based on all the barriers identified for measures not installed in the 2988 HRCP homes. Only those that accounted for 20% or more of the total barriers for each measure are shown.

[b]These contract restrictions refer to the four auditor-installed measures and were generally cited for water heater wraps. Thus, the 227 outlet gaskets not installed because of this barrier were actually not installed because the absence of a pressure relief valve on the water heater prevented installation of 370 water heater wraps.

[c]These six barriers accounted for 90% of all those cited; the remaining 26 barriers accounted for the other 10%.

A noncompatible structure or heating system frequently prevented recommendation and/or installation of heating duct insulation and clock thermostats. Houses with individual room electric heaters (68% of the total) cannot have duct insulation or clock thermostats installed.

Insulated doors were frequently identified as not cost-effective during the energy audit. HRCP policy defined thermal doors as inappropriate unless the existing door was in poor condition. This explains why this measure was recommended and installed less frequently than any other measure. Storm windows were often identified as not cost-effective during the contractor bid phase.

Outlet gaskets, water heater insulation, water heater pipe wrap, and low-flow showerheads were not installed under certain circumstances, spelled out in the contract between HRCP and the auditors. For example, water heater wraps were often not installed because the water heater did not have a pressure relief valve. Until their instructions were clarified, auditors installed none of the four low-cost measures if the water heater did not have a pressure relief valve. This explains the high percentages for contract restriction (Table 12) for these measures.

NONINSTALLED MEASURES: RECOMMENDED VS NOT RECOMMENDED

About 51% of the measures were not installed in the 2988 homes considered here. Roughly 20% of these noninstalled measures were recommended during the energy audits, while the remaining 80% were neither recommended nor installed. Here we examine differences in the types of barriers between these two sets of noninstalled measures.

For the measures recommended but not installed, existing installation accounted for more than half the total (Fig. 13). In many of these cases, the barrier noted was not cost-effective (NCE), identified during the contractor bid. Ceiling and floor insulation were the two measures most frequently recommended but not installed; these two measures accounted for more than 40% of all the NCE measures. In many other cases, physical limitations were uncovered by the contractor that prevented installation of the recommended measure, accounting for 36% of the measures recommended but not installed.

Measures were frequently not recommended at all because of physical limitations (30%) or because the measure would not be compatible with the structure or heating system (25%).

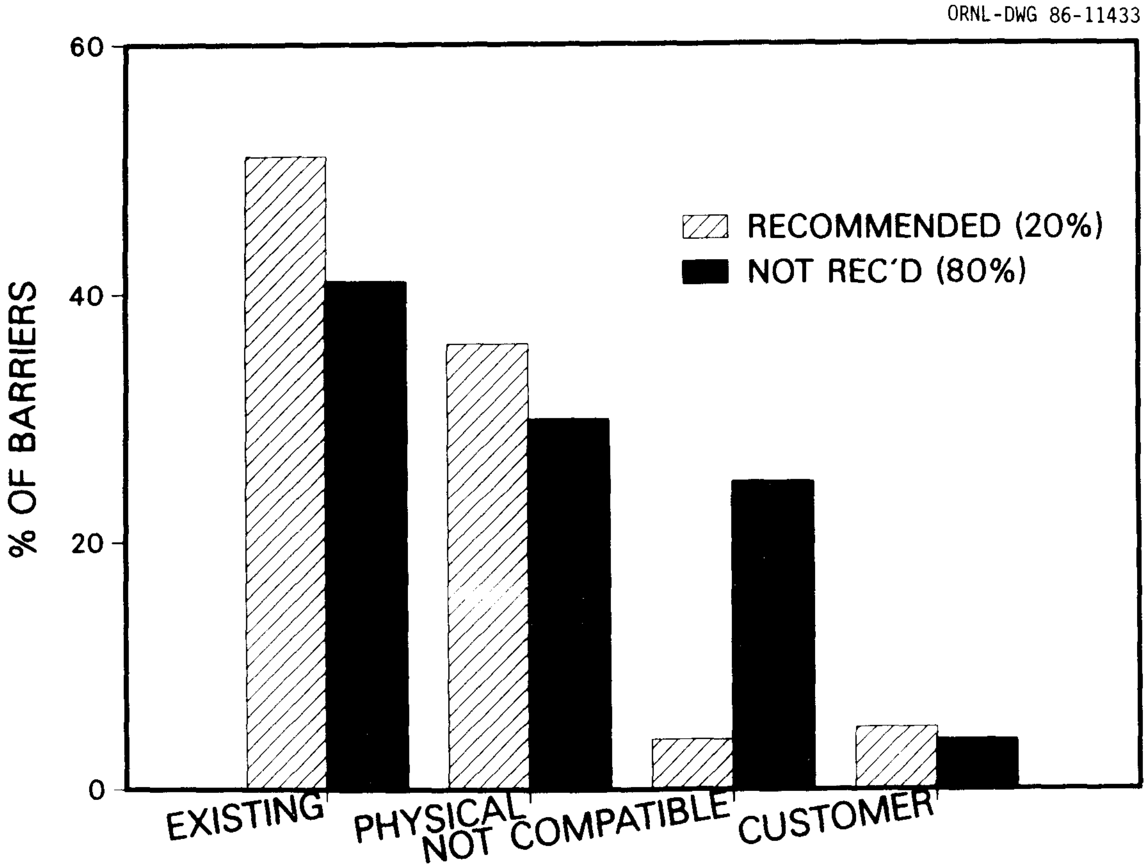

Fig. 13. Distribution of barriers for noninstalled measures, recommended vs nonrecommended measures.

RECOMMENDED MEASURES: INSTALLED VS NONINSTALLED

As noted earlier, 17% of the measures recommended during the energy audit were not installed by HRCP (Table 4). Examination of the estimated energy savings for these measures provides some explanation of why they were not installed. For all the insulation and glass measures, the ratio of estimated energy saving to cost was relatively low. For measures that were installed, the ratio was much higher. In other words, rejected measures, on average, were expected to save less energy than installed measures; almost 60% of these measures were rejected because they did not meet the Project's cost-effectiveness limit (NCE; Fig. 13). This difference was most dramatic for the insulation measures; measures that were not installed typically would have saved only half as much electricity as the measures that were installed.

5. DISCUSSION

Presentation and analysis of data on retrofit measures installed by HRCP demonstrate the enormous richness and value of the HRCP data base. Clearly, HRCP and its extensive and competent data collection yield valuable and unique information on residential retrofit in the Pacific Northwest. These data form the basis for a variety of analyses that will provide important new insights concerning the design, operation, and success of residential retrofit programs. This and subsequent reports will use the HRCP data to analyze participation in the Project, installation of retrofit measures, and actual energy and load reductions. The HRCP data are also being used for analysis of residential wood use, postretrofit changes in indoor temperatures, actual electricity savings produced by installation of water heating conservation measures, and comparison of actual savings with audit predictions.

The high level of HRCP retrofits and the substantial financial contribution minimize the importance of existing levels of structure thermal performance and capital cost, two major obstacles to retrofit in most conservation programs. Removal of these barriers, coupled with the details provided on types and times of barriers, greatly increases our knowledge of the practical limits of residential retrofit programs in terms of both participation in such programs and adoption of recommended measures.

HRCP was remarkably successful in getting recommended measures installed. Of the measures recommended by the HRCP energy auditors, 83% were subsequently installed by the Project. These installed measures accounted for 93% of the estimated electricity savings. These results demonstrate the feasibility of installing most of the recommended measures in a program that is well run and that pays for virtually all of the retrofit cost.

The conservation potential in existing homes is difficult to define and to determine. Different definitions are possible depending on how one considers measures that are not applicable, that cannot be installed because of physical limitations, that are already partially or fully in place, or that residents do not want installed.

Accurate determination of conservation potentials requires detailed data on the current condition of the region's housing stock. This includes information on existing levels of conservation measures, types of structure and heating equipment, physical barriers that prevent installation of otherwise needed measures, and installation cost. HRCP data show the importance of these factors; almost half the measures hypothetically applicable were not recommended because of these factors (and therefore not installed).

HRCP succeeded in gaining participation from more than 90% of the eligible households (3249 of 3500 signed up for the Project). HRCP was also sucessful in installing more than 80% of the retrofit measures recommended. However, it is too soon to know whether the Project is actually saving energy and reducing electrical loads as anticipated. Information on actual kWh and kW reductions must wait until sufficient postretrofit electricity billing and load metered data are available, in Fall 1986.

ACKNOWLEDGMENTS

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DETERMINANTS OF ELECTRICITY USE FOR RESIDENTIAL WATER HEATING: THE HOOD RIVER CONSERVATION PROJECT*

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ABSTRACT

Because 85% of the homes in the Pacific Northwest have electric water heaters, water heating is the second most important residential electricity end-use in the region (second to space heating). This paper analyzes the determinants of water-heating electricity use, using end-use load data and responses to a detailed home interview. These data are available for 142 homes in Hood River, Oregon.

On average, these homes used 5000 kWh/year for water heating. Almost 60% of the household-to-household variation in electricity use was explained with eight variables in a simple regression model. The number and ages of household members are the strongest determinants of electricity use: use increases by roughly 1000 kWh/year with each additional household member. Other statistically significant determinants of water-heating electricity use are hot-water temperature, water-heater location, number of showers in the home, and house type.

Electricity use varies considerably throughout the year (as well as across households). Weekly usage was 50% higher in mid-winter than in summer. About half of this temporal variation is due to changes in outdoor temperatures and half is due to seasonal changes in behavior (i.e., increased use of hot water in winter).

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1. INTRODUCTION

Water heating is the second largest user of energy in the residential sector, accounting for almost 20% of total U.S. residential end-use energy consumption (EIA 1985). Only space heating, which accounts for about half the total, consumes more energy.

Nationally, water heating is important to electric utilities for several reasons. First, a much larger percentage of residential customers use electricity for water heating than use electricity for space heating (32% vs 16% in 1982; EIA 1984). Second, several low-cost measures are available to reduce electricity use for water heating. Third, because of their large storage capacity, residential water heaters are frequently the focus of utility load management programs.

Electric water heating is particularly important in the Pacific Northwest, where about 85% of the homes use electricity for water heating; 45% use electricity as the primary heating fuel (BPA 1984). Analyses conducted by the Northwest Power Planning Council (NPPC 1983) suggest that water heating accounted for 26% of total residential electricity use in the Pacific Northwest during 1981, compared with 31% for space heating. The Council estimated the cost-effective potential to reduce electricity use for water heating at 514 MW; these savings represent better-insulated water-heater tanks, pipe wraps (insulation on the hot and cold water pipes connected to the water heater), and more efficient hot-water-using appliances (NPPC 1986). The achievable portion of this is 377 MW, 18% of projected water-heating electricity use in 2005.

This paper presents results from the first of a two-phase project. The purpose of the project is to analyze the level and determinants of annual residential water-heating electricity use and the determinants of electricity savings due to installation of water-heating conservation measures.

The data used here are from the Hood River Conservation Project (HRCP), a major residential retrofit demonstration project, sponsored by the Bonneville Power Administration (BPA) and administered by Pacific Power & Light Company (PP&L). The first phase uses data collected from 142 homes in Hood River during the July 1984 - June 1985 period, before retrofits were installed in these homes. Thus, the present paper analyzes baseline patterns and determinants of electricity use. The second phase, which will use data from both pre-and post-retrofit periods (July 1984 through June 1986), will analyze electricity savings due to installation of water-heating conservation measures and analyze the factors that explain variations across households in these savings.

The following section briefly reviews prior studies of residential energy use for water heating. Section 3 discusses the determinants of residential electricity use for water heating from a theoretical perspective. Section 4 describes the data available from HRCP for this project, and Section 5 uses these data to develop empirical results concerning cross-sectional variation in water-heating electricity use. Section 6 demonstrates the temporal variation in electricity use for water heating and develops a simple model to explain this variation as a function of outdoor temperature and season. The final Section summarizes our findings and discusses the forthcoming second phase of the project.

2. PRIOR STUDIES

Several empirical and analytical studies of energy use for water heating have been conducted during the past decade. Early studies (A.D. Little 1977, Hirst and Hoskins 1977) focused on theoretical estimates of likely energy savings due to more efficient water heater designs. Other studies (A.D. Little 1977; Palla 1979; Ek 1982; Biemer, Auburg and Ek 1985) included experiments to measure energy savings in a laboratory environment. Some recent studies (summarized in Usibelli 1984) include field-test data on water-heater energy use. None of the studies we reviewed analyzed the factors that influence energy savings due to these conservation measures (e.g., location of the water heater, number of people in the household).

Many utilities have measured electricity use for water heating by time of day (usually at 15-minute intervals). For example, a major project conducted by Gilbert Associates (1985) for the Electric Power Research Institute, collected load research data on water heaters in 110 homes from 11 utilities in 10 states throughout the U.S. The Gilbert project included detailed data on water consumption as well as electricity use, plus information on household demographics and the characteristics of the monitored water heaters. Most load research projects, however, are characterized by very small sample sizes (which are therefore not representative of any larger population) and very limited information on household demographic and economic characteristics (e.g., TVA 1982).

The performance of alternative water-heating technologies such as solar systems, heat pump water heaters, and waste heat recovery units has been measured and analyzed in several projects. Although results vary substantially across these projects, heat pump and solar water heaters generally consume only half as much electricity as do conventional water heaters (Florida Solar Energy Center 1983, TVA 1984, Hanford et al. 1985).

A group at Michigan State University is monitoring the water-use patterns in six homes (Kempton 1984; Weihl and Kempton 1985). Their studies combine detailed engineering data collection on water-heating electricity use and hot water consumption by point of use with onsite home interviews to understand household patterns of hot-water use.

Finally, economists have analyzed whole-house energy use (generally with monthly energy bills) to statistically disaggregate energy use by end-use. This conditional demand approach (CDA) can be used to estimate energy use for individual end uses if there is sufficient variation across households in their appliance holdings; in some cases, colinearity among explanatory variables makes it difficult to interpret the coefficients estimated with CDA models (Latta 1983). Lawrence and Parti (1984), in their review of several CDA studies, noted that the number of household members, household income, and fuel price were the major factors used to explain house-to-house variations in energy use.

3. DETERMINANTS OF WATER-HEATING ELECTRICITY USE

Electricity is used for water heating in two ways: to heat water from its inlet temperature to the desired hot-water temperature for consumption (recovery) and to maintain the hot-water temperature at the desired level in the water-heater tank (standby losses). A.D. Little (1977) estimated that about 17% of the annual electricity use for residential water heating was to compensate for standby losses, implying an overall energy-efficiency of 83%. Hirst and Hoskins (1977) accounted for standby losses through distribution pipes and estimated an efficiency of 81% (14% lost through the jacket plus 5% through the pipes). Usibelli (1984) notes that the average efficiency of new electric water heaters remained nearly constant (at about 80%) between 1972 and 1980.

Electricity use for hot-water consumption depends on the household's appliance holdings (clothes washer, dishwasher, and number of baths and showers), use of these appliances, and the difference between inlet and outlet water temperatures. Appliance use (e.g., number of loads of laundry washed per week) depends on season and on household characteristics, especially the number and ages of occupants. Appliance holdings are influenced by household demographics including income and number of occupants. The design of appliances can also affect their hot-water consumption (e.g., water-saver cycles on washing machines, low-flow showerheads). Finally, inlet water temperatures depend primarily on climate, while outlet temperatures are determined by the household (through selection of the hot water thermostat setting).

Standby losses depend on the physical characteristics of the water heater and its location. The larger the tank, the larger will be the standby loss; the greater the amount of insulation on the tank and on the inlet and outlet pipes, the less will be the standby loss. Standby loss is proportional to the difference between tank-water temperature and the ambient temperature around the water heater (which is a function of the water heater's location). Thus, tanks located in unheated basements, crawl spaces, or garages are likely to have greater standby losses than tanks located in conditioned spaces inside the house.

4. HRCP DATA USED IN THIS PROJECT

The data used here to analyze electricity use for residential water heating are from the Hood River Conservation Project. HRCP is a $21 million, three-year residential retrofit demonstration project. The Project is intended to define the maximum limits of a utility-operated residential retrofit program, one in which cost to participating households is not a barrier and in which the level of retrofit measures installed is beyond that conventionally installed (PP&L 1983).

Because HRCP is an ambitious and complicated project, the data associated with the project are correspondingly extensive and detailed. Perhaps more important, the project's focus on research requires collection of extensive data.

Detailed electricity end-use data are being obtained from 319 homes in Hood River. Information on total, space heating, and water heating electricity uses as well as indoor temperatures is collected at 15-minute intervals in these homes. Wood heat sensors are used in place of the water-heating electricity-use monitors in 100 of these homes (Oliver et al., 1984). These data are being collected for a period of at least two years, beginning in Spring 1984. Because these 319 homes were all retrofit in mid-1985 (May through July), a full year of preretrofit data and at least one year of postretrofit data will be available for analysis. The present project uses daily totals of the first year of data (July 1984 through June 1985) from the water heater channel.

Data at a comparable level of temporal detail (15-minute intervals) are collected at three weather stations in Hood River. The primary weather station is at the same location as the National Oceanic and Atmospheric Administration (NOAA) Hood River Experiment Station. We used daily outdoor temperature (Tout) data from NOAA (e.g., NOAA 1984) in the present analysis.

The Project collected information on household demographics and appliance holdings at the time of the energy audit. The audit yielded estimates of the applicable retrofit measures, their likely energy savings and expected costs. These data on the three water-heating measures (water heater wrap, pipe wrap, low-flow showerheads) will be analyzed in the second phase of this project.

A detailed onsite home interview was conducted in July 1984 among the load-metered homes. This interview, which used the same questionnaire used in the 1983 Pacific Northwest Residential Energy Survey (BPA 1984), included detailed questions on the demographic characteristics of these households, the characteristics of their dwelling units and appliances, heating fuels, and other energy-related attributes. This data is used here to explain differences across households in annual electricity use for water heating.

Although 210 homes were load metered with a water-heater channel, data on only 142 were used in this analysis. Twenty-two households had more than 35 days of missing water-heater channel data,* reducing the total to 188. Other cases were deleted from the sample for various reasons:

more than nine days of water-heater channel data were zero,
missing or zero data for the whole-house channel,
the household survey was missing,
the water heater was in a multifamily building with five or more dwelling units, or
the home used an additional fuel for water heating (generally wood).

*See Hirst and Goeltz (1986) for an explanation of the method used to impute values for daily load when missing.

5. ANALYSIS OF ANNUAL ELECTRICITY USE FOR WATER HEATING

SUMMARY STATISTICS

Averaged over the 142 homes in this data set, electricity use for water heating was 5040 kWh/year (July 1984 through June 1985). Use ranged from a low of 1400 kWh to a high of 15,800 kWh. Six households used more than 10,000 kWh/year and eight used less than 2000 kWh for water heating (Fig. 1).

Using annual energy use data from the 1980 Residential Energy Consumption Survey, conducted by the Energy Information Administration, Latta (1983) statistically estimated average electricity use for water heating at 3500 kWh/year. Usibelli's (1984) data suggests an average of 4900 kWh, while the average usage among the 110 homes in the Gilbert Associates (1985) load research project was 6000 kWh. Thus, the Hood River average is within the range of other studies.

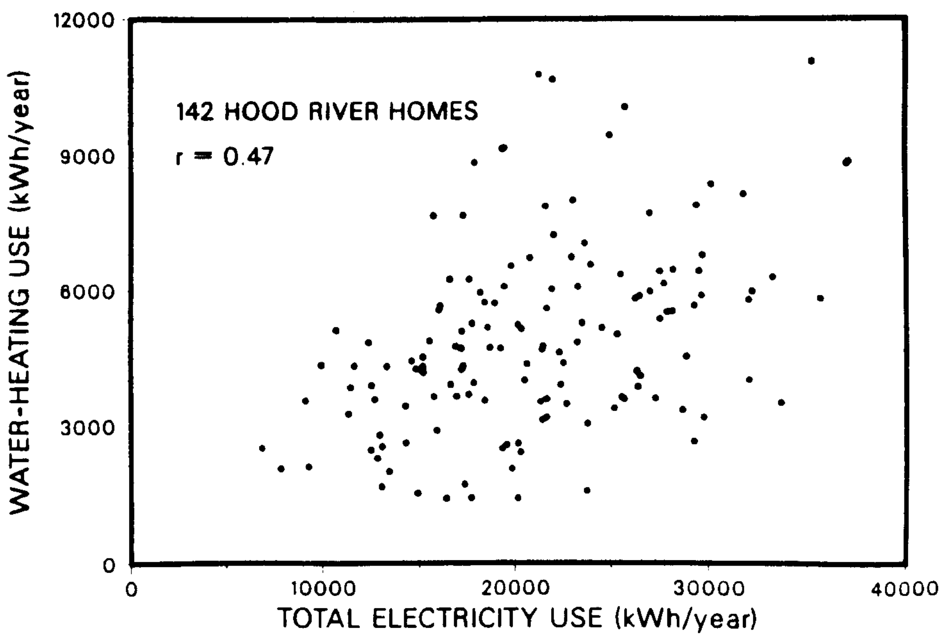

Fig. 1. Water heating electricity use (kWh/yr) as a function of total use in 142 Hood River homes. Six homes used more than 10,000 kWh for water heating and three used more than 40,000 kWh total; these nine homes are not shown in the figure.

On average, water-heating electricity use accounted for 24% of total electricity use in these homes, very close to the 25% found by Gilbert Associates (1985). The percentage varied substantially across the Hood River homes, from 7% up to 51% (Fig. 1). This large range is a consequence of both the variation in electricity use for water heating and the variation in electricity use for space heating (e.g., many homes in Hood River use wood for some of their space heating).

As discussed above, electricity use for water heating depends strongly on the number of people in the household (Table 1). Electricity use increases nonlinearly with number of occupants - in general, each additional household member has a smaller incremental effect on electricity use.

Table 1. Water heating electricity use as a function of household size in Hood River

Number of household members	Number of homes	Electricity use (kWh/year)	
		Mean	Std. dev.
1	19	2600	880
2	56	4290	1560
3	22	5460	1260
4	31	6190	1920
5	8	7400	2430
6 or more	6	9270	3720
Average		5040	2320

Electricity use also depends on the location of the water heater (Table 2). Units located in a heated area use about 500 kWh/year less than units in unconditioned spaces.* Water heaters in mobile homes use

*Standby losses from water heaters located in conditioned spaces reduce energy use for space heating (Corum 1986). Assessments of improvements in water heating efficiency should consider the effects on space heating and air conditioning also.

almost 400 kWh/year less, on average, than do water heaters in single-family homes; this may be due, in part, to the fact that the number of occupants is lower in mobile homes. (Hot water tanks may also be smaller in mobile homes; we have no data on tank size.)

. The HRCP data show no relationship between electricity use and presence of a water-heater insulation blanket or low-flow showerheads.* This lack of (expected) energy savings may be due to correlations between presence of these conservation measures and other factors that affect electricity use. For example, homes with low-flow showerheads tend to have more occupants. Similarly, hot-water outlet temperature and presence of these two conservation measures is correlated. In principle, it should be much easier to statistically identify the electricity savings due to these conservation measures with the pre- vs post-test load data (phase 2 of this study) than with the present cross-sectional data across households.

Table 2. Water heating electricity use in Hood River

	Electricity use (kWh/year)
Water heater location	
Heated area	4780
Unheated area	5310
Housing type	
Single-family	5130
Mobile home	4740

*There is, however, considerable empirical evidence that these measures reduce water-heating electricity use (e.g., Usibelli 1984; Biemer, Auburg and Ek 1985; Palla 1979). The savings for water-heater wraps are about 500 kWh/year, for low-flow showerheads about 400 kWh, and for pipe wrap about 60 kWh.

Interviewers measured hot water temperatures during the 1984 onsite home interviews. Temperatures ranged from 110°F to 185°F, with a mean of 131°F. As expected, there is a statistically significant correlation between electricity use and water temperature ($r = 0.38$).

CROSS-SECTIONAL ANALYSIS OF ELECTRICITY USE

The preceding section summarized the data available on water-heating electricity use and its determinants. Here, we analyze the data using cross-sectional multivariate models of annual electricity use.

Based on the discussion in Section 4, we tested several explanatory variables, some of which were statistically insignificant. Dummy variables for ownership of clothes washer or dishwasher had no effect on electricity use; perhaps there is little difference in water consumption between hand and machine washing. Income, education of household head, insulation on the water heater, and low-flow showerheads were all insignificant. These variables were dropped from the final model.

The final model (Table 3) included eight explanatory factors: the number of occupants by age group (small children, school-age children, adults, and elderly), hot-water temperature, number of showers in the home, and binary variables for water-heater location (unheated vs conditioned space) and housing type (mobile home vs single-family). All of these variables, except for the number of small children, were significant at the 5% level or better.*

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*Examination of the residuals (i.e., a plot of residuals vs predicted electricity use) showed no patterns, suggesting that heteroskedasticity is not a problem with this model. Similarly, the correlation coefficients among the explanatory variables were low, suggesting that multicolinearity was also not a problem. The only nontrivial correlation was between the number of occupants older than 65 and the number between 18 and 65 years ($r = -0.63$).

Table 3. Regression results from model of annual electricity use for water heating

Explanatory variable	Model coefficient	t statistic
Intercept	-2808	1.5
Number of household members, by age (years)		
< 6	339	0.9
6 - 18	894	5.7
18 - 65	1073	7.0
> 65	705	2.5
Hot water temp (°F)	35.0	2.4
Number of showers in home	686	3.2
Binary variables for:		
Water heater in heated area	-535	2.0
Mobile home	-741	2.3

[a]Based on 142 observations; model $R^2 = 0.57$.

Model results show that the number of household members has a substantial and positive effect on electricity use. Interestingly, the influence of adults (18 - 65 years old) is greater than that of any other age group; the number of children less than 6 years old has no statistically significant effect on electricity use.

The hot-water temperature coefficient suggests that electricity use decreases by 35 kWh/year for every 1°F decrease in hot water temperature. Thus, reducing the thermostat setting from 140° to 120° should cut electricity use by 700 kWh, in close agreement with laboratory tests (Palla 1979) and calculations (A.D. Little 1977; Hirst and Hoskins 1977).

The number of showers in the home is positively related to electricity use. This variable is probably capturing the effects of other factors that influence electricity use for water heating. For example, the number of showers is positively correlated with presence of a dishwasher, house size, number of adults, and household income.

Water heaters located in conditioned spaces use, all else equal, 540 kWh/year less than units in unheated areas. Thus, the standby loss (about 20% of 5000 kWh) can be roughly cut in half by placing the water heater inside the heated portion of the house. Finally, water heaters in mobile homes consume 740 kWh/year less, on average, than do units in single-family homes. Mobile home occupants generally have lower incomes and are less likely to have a dishwasher, both of which contribute to the negative coefficient for this variable.

We tested a model that included both linear and squared terms for the number of occupants. The additional (squared) terms were statistically insignificant; an F-test showed that they did not improve model performance. Thus, although our prior discussion (as well as intuition) shows that electricity use increases less than linearly with number of household members, we are not able to statistically identify this pattern, at least not for separate age groups.

6. TEMPORAL VARIATION IN WATER-HEATING ELECTRICITY USE

Electricity use for water heating varies considerably during a typical year (Fig. 2). Mean weekly electricity use in the winter is roughly 50% higher than in the summer. This temporal variation occurs because households use more hot water in winter than in summer and because ground water temperatures are lower in winter. Thus, the dynamics of water-heater electricity use depend on both seasonal behavior and weather.

The data collected by Gilbert Associates (1985) from 11 utilities showed average daily hot water consumption per household of 70 gallons in January, compared with 57 in July.* In addition, electricity use per

*Data from the Tennessee Valley Authority show that hot water use is about 20% higher in winter than in summer (Sanders 1986), consistent with the Gilbert findings.

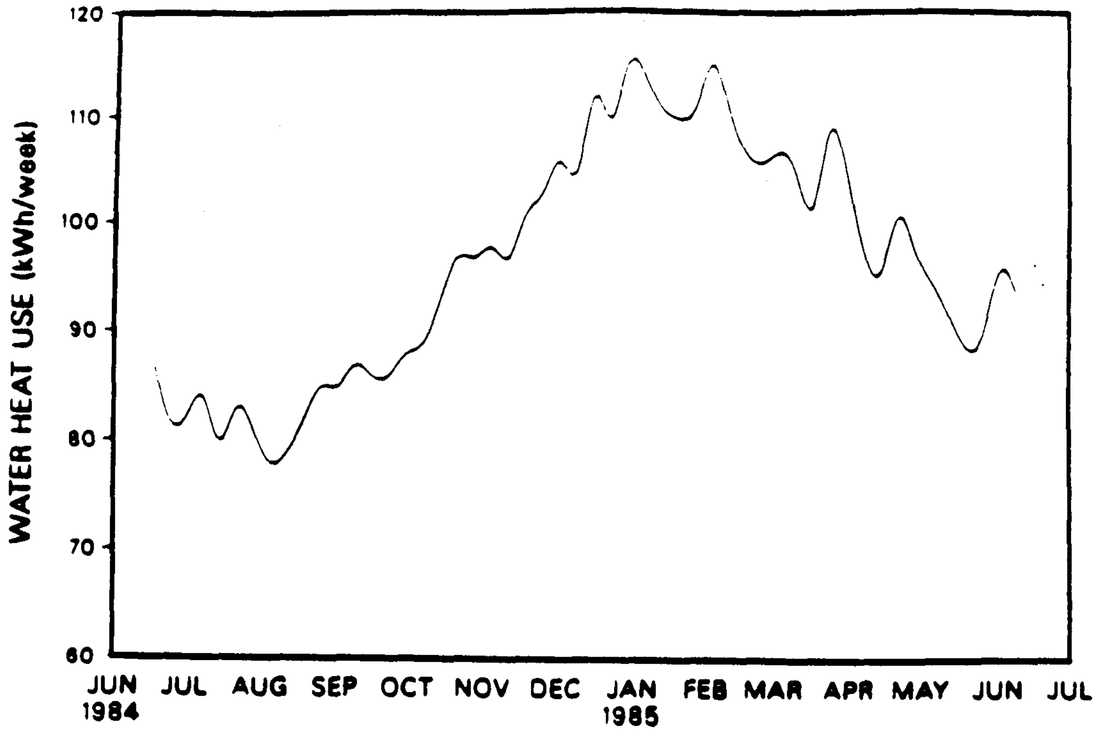

Fig. 2. Mean electricity use (kWh/week) for water heating among 142 homes in Hood River, Oregon.

gallon of hot water consumed was almost 50% higher in January than in July. Inlet water temperatures (averaged across the 11 utilities) reached their minima in February (51°F) and their maxima in August (71°F), lagging changes in air temperatures by roughly one month.

Understanding the dynamics of electricity use and the factors that affect these temporal changes is important. For example, efforts to weather-normalize household electricity use implicitly assume that outdoor temperatures are the major determinants of short-run changes in electricity use (Burnett and Lesser 1985; Hirst and Goeltz 1986; Fels 1986). If some of these changes in electricity use are independent of weather, then weather-normalization methods will overcompensate.

To analyze the dynamics of water-heating electricity use, we estimated a nonlinear regression model* of weekly electricity use. The model used the mean value of electricity use over all 142 homes as the dependent variable:

$$\text{WH (kWh/week)} = a + b*\text{Tout} + c*\text{Sin}[(t - d)\,\pi/26]\ , \qquad (1)$$

where Tout is ambient (outdoor) temperature,** obtained from NOAA; t is time in weeks, with t = 1 referring to the first week in July; and a, b, c, and d are coefficients estimated by the model.

Physically, $a + b*\overline{\text{Tout}}$ is the mean value (averaged over the entire year) of water-heating electricity use. The term, b*Tout reflects the temperature- (weather-) dependence of electricity use. The last term in the equation captures the seasonal variation in hot water usage.

Estimation of this model [using Proc NLIN in SAS (1985)] yields:

$$\text{WH (kWh/week)} = 115 - 0.374*\text{Tout} + 8.77*\text{Sin}[(t - 21.9)\,\pi/26]\ ,$$

with 52 weekly observations; $R^2 = 0.96$. These results show a mean value of 97 kWh/week, implying an annual usage of 5040 kWh (in perfect agreement with the actual mean value noted in Section 5). The hypothetical maximum weekly use, at the time of minimum outdoor temperature (24°) and the 35th week after July 1 (early March), is 145 kWh and the hypothetical minimum, at the time of maximum outdoor temperature (71°) and 9th week (early September) is 79 kWh.

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*Palmiter (1986) suggested that a multiplicative, rather than additive, model might better explain the temporal variation in electricity use. He also pointed out that eqn. 1 can be made linear by using both Sine and Cosine terms.

**We plan to test soil temperatures (as an alternative to Tout) during phase 2 of this project. Soil temperatures (which vary less throughout the year and lag outdoor temperatures) may be more closely correlated with inlet water temperatures, especially for homes that draw water from wells.

Rewriting the model to normalize the outdoor temperature term (so that it varies from +1 to -1) yields:

WH (kWh/week) = 97 - 8.8[(Tout - 50)/24] + 8.8*Sin[· · ·] ,

where 50°F is the mean outdoor temperature over this 52-week period. Normalizing the outdoor temperature term in this fashion shows that variations in electricity use are due equally to changes in outdoor temperature and seasonal behavior (i.e., the two coefficients are equal).

One problem with this model is the close correlation between the two explanatory variables; the temperature and sine terms have a correlation coefficient of r = -0.82. Thus, the model suffers from multicolinearity, a problem that can be resolved only by using data from several locations in different climate zones.

Because of the correlation among explanatory variables, we estimated a simpler model:

WH (kWh/week) = a + b*Tout . (2)

The R^2 for this model was lower than for the original model (0.85 vs 0.96), with a = 134 and b = -0.76. Rewriting the model yields:

WH (kWh/week) = 96 - 18*[(Tout - 50)/24] .

Note that both the mean value and time-varying terms are virtually identical for the two models. The similarity in results indirectly confirms the colinearity problem noted above.

We next estimated eqns. 1 and 2 for each of the 142 households individually.* On average, model performance was terrible. For example, the mean value of R^2 over the 142 models associated with eqn. 2 was only 0.25. Almost 10% of these household-level models had b coefficients with a positive slope (suggesting less electricity use in winter than in summer).

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*We could have estimated a pooled time-series/cross-section model with 7384 observations (142 households x 52 weeks), but there is no temporal variation in the demographic and dwelling-unit data.

To better understand the dynamics of water-heating electricity use for individual households, we examined plots of weekly electricity use for each of the 142 homes in the HRCP data base. Although many of the homes exhibit patterns similar to that of the average (Fig. 2), many homes show very different patterns.

For example, some homes show multiweek periods of near-zero use, perhaps while the family is on vacation. Some homes show a few weeks (not necessarily contemporaneous) with very high electricity use, perhaps while friends or relatives are visiting. Some homes show very little seasonal variation, perhaps because their water is obtained from deep wells and therefore has nearly constant temperature year-round.

7. DISCUSSION

We used data from 142 homes in Hood River, Oregon to examine electricity use for water heating. The data available for this study included daily summaries of 15-minute water-heater electricity loads from July 1984 through June 1985. Results of a detailed home interview with each of these households were also available for analysis. Finally, daily averages of outdoor temperature were available from the NOAA weather station in Hood River. These data were collected as part of the Hood River Conservation Project, a major residential retrofit program in the Pacific Northwest.

Analysis of annual aggregates of the electricity use data, with a cross-sectional multivariate regression model, showed that the number and ages of household members are the strongest determinants of hot-water electricity use. On average, electricity use increases by about

1000 kWh/year with each additional household member. Adults (18 - 65 years old) have more influence on electricity use than do older residents or children.

Hot water temperatures (as measured by interviewers during the on-site home interviews) also affect electricity use. Each 1°F decrease in temperature yields a 35 kWh/year decrease in electricity use.

Finally, the model showed that electricity use increases with the number of showers in the home, and is affected by water-heater location and house type.

Electricity use for water heating varies considerably throughout the year; weekly usage was about 50% higher in mid-winter than in summer. Preliminary analysis of this temporal variation suggests that about half is due to changes in outdoor temperatures (which affect inlet water temperatures and the temperature of the ambient air surrounding the water heater) and half is due to seasonal changes in behavior (higher consumption of hot water in winter than in summer). This analysis is considered preliminary because the seasonal and outdoor-temperature effects are highly correlated.

A second phase of this project is planned for late 1986. At that time, an additional year of water-heater channel data will be available. This postretrofit data (July 1985 through June 1986) will permit explicit analysis of the energy-saving effects of the water heating conservation measures installed in these homes during mid-1985. The additional year of data, plus use of outdoor and soil temperatures from the three HRCP weather stations might permit clearer decomposition of the seasonal and temperature dependence of water-heating electricity use.

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