COMPARISON OF THE PERFORMANCE AND ENERGY SAVINGS POTENTIAL OF HEAT PUMP, SOLAR, AND CONVENTIONAL WATER HEATERS IN THE PACIFIC NORTHWEST

J. A. Bamberger[a], R. C. Hanlen, B. A. Le Baron,
W. L. Nicholson and P. W. Zimmerman
Pacific Northwest Laboratory

B. Cody
Bonneville Power Administration

ABSTRACT

Electricity consumed by water heaters represents 20 to 30% of residential annual electricity consumption. Bonneville Power Administration designed a study to compare electrical consumption of conventional resistance water heaters to electrical consumption of solar and heat pump water heaters in the Pacific Northwest. The basis of comparison is electrical consumption and demographic data collected by Bonneville Power Administration and the Oregon Department of Energy (ODOE). The energy savings potential for the technologies is evaluated and categorized by site characteristics, climate or solar zone, family size, and water heater type. The data are adjusted for occupancy level and site descriptor variables (covariates), including age and income level of occupants, the presence of dishwashers and flow restrictors.

The estimated annual electrical usage of heat pump and solar systems is 21 to 62% lower than conventional systems, with solar systems saving more than heat pump systems. With the cost of electricity at $0.04/kWh, the expected savings for heat pump water heaters compared to the conventional water heaters is $33 per year in climate zone 1. The expected savings for solar water heaters compared to conventional water heaters is about $50 per year and is dependent upon the solar zone.

(a) Please address correspondence to J. A. Bamberger, Pacific Northwest Laboratory, P.O. Box 999, Richland, Washington 99352, (509) 375-3898.

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INTRODUCTION

Electricity consumed by water heaters represents 20 to 30% of residential annual electricity consumption. This investigation compares the annual electrical energy consumption of three types of water heating systems installed in the Pacific Northwest: heat pump water heaters, solar water heaters, and conventional electrical resistance water heaters (Bamberger 1987). Previous research on the actual configuration of these technologies in field settings has failed to produce definitive results of estimated energy savings (Biemer 1984, Hanford 1985a,b, Harris 1985). In addition no major field studies were conducted in the Pacific Northwest. The monitored heat pump and solar water heater data from the Oregon Department of Energy (ODOE) will provide the basis for a reliable estimate of energy savings for heat pump and solar hot water systems[a]. The other key element in the analysis is submetered consumption of electrical energy used for heating water in similar households without these technologies.

The primary use of this analysis will be to support Bonneville's solar and heat pump water heater market test, which will measure the effects of advertising versus traditional cash incentives in the promotions of these water heating systems. A reliable estimate of electrical energy savings is needed to calculate program cost to Bonneville and the region per estimated kilowatt-hour saved. To estimate energy savings potential in the Pacific Northwest, the energy usage for each technology was evaluated and categorized by various site characteristics, climate or solar zone, family size, and other demographic parameters. To determine whether the estimate of energy savings during the study period is typical or atypical, meteorological conditions during the study period were evaluated.

WATER HEATER DATA

Three data sets form the basis for the comparison between conventional, heat pump, and solar water heaters. The solar and heat pump sites were metered by the Oregon Department of Energy (ODOE). The conventional sites were metered by the Residential Standards Demonstration Program (RSDP) Triple

(a) For additional information about the ODOE data set see Robison (1988 and 1987).

Metered study and the Hood River Conservation Project (HRCP). Data available from each study set were reviewed to identify information common to all data sets and information necessary for a thorough analysis.

The ODOE data base was obtained from solar and heat pump water heater sites' instrumented electric meters and water meters which were read by the occupants once a month. The meters were reliable and accurate within 1%, but the overall accuracy depends on the recorded data. If digits were misread or transposed, the error of a single reading could be high. The accuracy is expected to be close to the equipment accuracy because the readings were cumulative.

The RSDP Triple Metered data base are similar to the ODOE data in terms of collection method and quality but cover a wider geographic area.

The Hood River data base was obtained from electrical loggers collecting data in 15 minute intervals for total electricity consumption, space heating consumption and water heating consumption. Hood River data have high reliability. Data accuracy is within 5%.

Heat Pump Water Heater Data

ODOE Heat Pump, Hood River and RSDP Triple Metered data from climate zone 1 were used in the heat pump versus conventional water heater analysis. Table I contains a summary of the apportionment of 478 residential sites by occupancy level and data set. Most of the 101 ODOE heat pump sites were located in Portland, Oregon. The 254 RSDP Triple Metered sites are scattered from western Washington (Seattle area) down to western Oregon (Portland, Salem and Medford). These areas are assumed to have similar climate conditions. From the tally of sites with occupancy level, we decided that it was worthwhile to view occupancy level as four distinct categories.

Table I. Tally of heat pump residential sites by data set.

Occupancy Level	ODOE Heat Pump	Hood River	RSDP Triple Metered	Total
1/2	28	68	96	192
3	18	15	62	95
4	34	30	80	144
5	21	10	16	47
Total	101	123	254	478

Solar Water Heater Data

The ODOE solar and RSDP Triple Metered data from solar zones 1, 2, and 3 were used in the solar versus conventional water heater analysis. Table II contains a summary of the apportionment of the residential sites by occupancy level, solar zone and data set. Most of the 271 ODOE solar sites are located in Eugene and Portland, Oregon with some also in Seattle, Washington. The quantity of data in solar zones 2 and 3 by occupancy level make the occupancy estimates within the solar zones tenuous. From the tally of sites within occupancy level, it was prudent to use only those occupancy levels here with the intent that we would probably not see anything of consequence with solar zones 2 and 3 for occupancy levels 3 and 4.

The ODOE solar data set included five types of flat plate collector systems. The system types are not specifically identified in the analysis because system sizes and installation arrangements, along with other variables, mask any potential difference in data for the different systems.

Table II. Tally of solar water heater analysis sites by solar zone, occupancy level and data set.

Occupancy Level	ODOE Solar				RSDP Triple Metered			
	Solar Zone				Solar Zone			
	1	2	3	Total	1	2	3	Total
1/2	93	11	23	127	94	60	11	165
3	51	4	8	63	62	39	9	110
4	61	6	14	81	77	56	15	148
Total	205	21	45	271	233	155	35	423

METEOROLOGICAL ANALYSIS

Climatic conditions vary with both time and geographic location. In this study, the spatial variation has been controlled by grouping sites with common temperature or solar characteristics into three climatic zones and three solar zones, respectively (Table III). The purpose of these groupings is to ensure that comparisons are made between sites in the same zone and will not be biased because of known climatic differences between zones. Any estimate of energy consumption for water heating devices reflect the efficiency of the devices as well as prevailing climatic conditions for the geographic region and time frame. A meteorological assessment of the July 1985 through July 1986 time frame was conducted to determine the effect on estimates of savings due to variation of climatic conditions from background (previous eight years).

Characterization of the temporal variation in climatic parameters is important when trying to establish relationships based on data collected over a limited time period. The meteorological analysis explores the uncertainty in the estimates of energy savings contributed by variation of the climatic conditions from normal weather conditions during the study period. The

Table III. Climate and solar zone definitions.

Climate or Solar Zone	Climate Zone Annual Degree Days, 65°F	Solar Zone Load Fraction
1	4,000 - 6,000	38 - 45%
2	6,000 - 8,000	47 - 56%
3	8,000 - 10,000	59 - 66%

climatic parameters that can most affect heat pump and solar water heater performance are air temperature and insolation, respectively. Thus, the issue of weather bias is based on an examination of monthly values of these two parameters. Temperature and insolation data are examined for the sites where the residences using heat pump and solar hot water heaters are concentrated. The examination of temperature and insolation variation covers July 1985 to July 1986, which is the time window chosen for the water heater data analysis. Ambient outside air temperature is used for temperature comparisons. Solar data for these comparisons are the total insolation on a horizontal surface. For the meteorological analysis, a period of 8 years (1977-1984) was selected as the base to establish the normal background variation for temperature and insolation at the study sites.

Temperature

The most significant deviation of the study period temperatures from the background normal occurs during November and December, 1985. During this period, nearly all sites exhibit below-normal temperatures, averaging 4.9°C below the background years. Subsequently, in the first quarter of 1986 the temperatures ran somewhat higher than normal. The only other noteworthy temperature deviations of the study period were July in both 1985 and 1986, when temperatures averaged 3°C above normal and 1.5°C below normal, respectively.

Insolation

Analysis of insolation data for all sites suggests that the study period experienced predominantly typical insolation when examined on a monthly basis. The notable exceptions are September 1985, when insolation for the sites located east of the Cascades was below normal, and the summer months of 1986, when insolation was approximately 8% above average in June, but subsequently 3% below average in July.

Summary

Based on comparisons of monthly mean daily insolation and temperature, with 8 years of background, the study period of July 1985 through July 1986 was not atypical, when considered in total. There are months, however, particularly for the temperature analysis, when significant deviations occur.

Based on this analysis, estimates of the electrical water heating energy saved by using solar or heat pump-assisted water heaters will be representative of savings for the normal year. Because temperatures were a little below normal for most of the study sites, it is conceivable that savings for heat pump water heaters could be slightly higher under normal conditions.

STATISTICAL ANALYSIS

Philosophy of Analysis

The data available for analysis in the study of heat pump and solar water heater energy usage presented some complex statistical issues to be resolved prior to evaluating the energy utilization versus conventional water heaters.

From a statistical design standpoint, one would like to have the water heater types located side by side in a residence, monitored so as to provide a paired comparison for electrical usage over a period of time. The data presented are from residences that had only one water heater of a specified type per residence. This means that the variation in electrical usage data from one residence to another is impacted by the amount of water heated by the water heater. This amount was not available to the analysts.

Since the amount of hot water usage was not available for all data sets, variables that are known to impact hot water usage were used to adjust for and reduce the residence to residence variation. This means that comparisons are made between residences that have similar occupancy, geographic characteristics, income level, and energy savings characteristics.

Even after the above adjustments are made, a variance stabilizing transformation was employed so that statistically valid tests could be employed for establishing the significance of results. Interpretation of modeled effects are for the average of a large number of residences after adjusting for variables that impact hot water usage. Thus, results presented represent the expected energy savings estimates for heat pump (or solar) water heater versus conventional water heaters for a large number of residences and not for a specific residence.

Analysis Procedure

The heat pump and solar analyses were conducted in three stages: 1) develop and view the typical residential energy usage time series, 2) construct an estimated annual usage (EAU) data set, and 3) perform an analysis of the EAU data set to determine estimates of the effect of using heat pump or solar devices to enhance water heating.

Residential water heater usage time series for all water heaters were developed for each data set by occupancy level and solar zone or climate zone to check for a temporal pattern in the data. For each residence in the study, a time series of daily energy use for water heating was constructed from the raw data. A smoothed time series was constructed from daily median values for each data set. Figure 1 is a plot of the smoothed time series for solar and conventional water heater daily electrical usage split out by solar zone for combined occupancy levels 1 and 2. It is obvious from figure 1 that the conventional water heater usage series is higher than the solar water heater usage (i.e., conventional units use more electricity than solar units) except possibly during the winter months. What is not displayed on the figure is the tremendous variation across residences that comprise the data set. This variation is important to get control of to establish the significance of the results. Also note that the smoothing operation is quite variable at the ends of the displayed time series as there are fewer residences reporting data.

For the solar water heater data a strong seasonal cycle was observed in each series, with low electrical usage in the summer and high electrical usage in the winter. Also, the winter peak usage is higher in solar zone 1 than in solar zones 2 and 3. The strong seasonal pattern is not surprising,

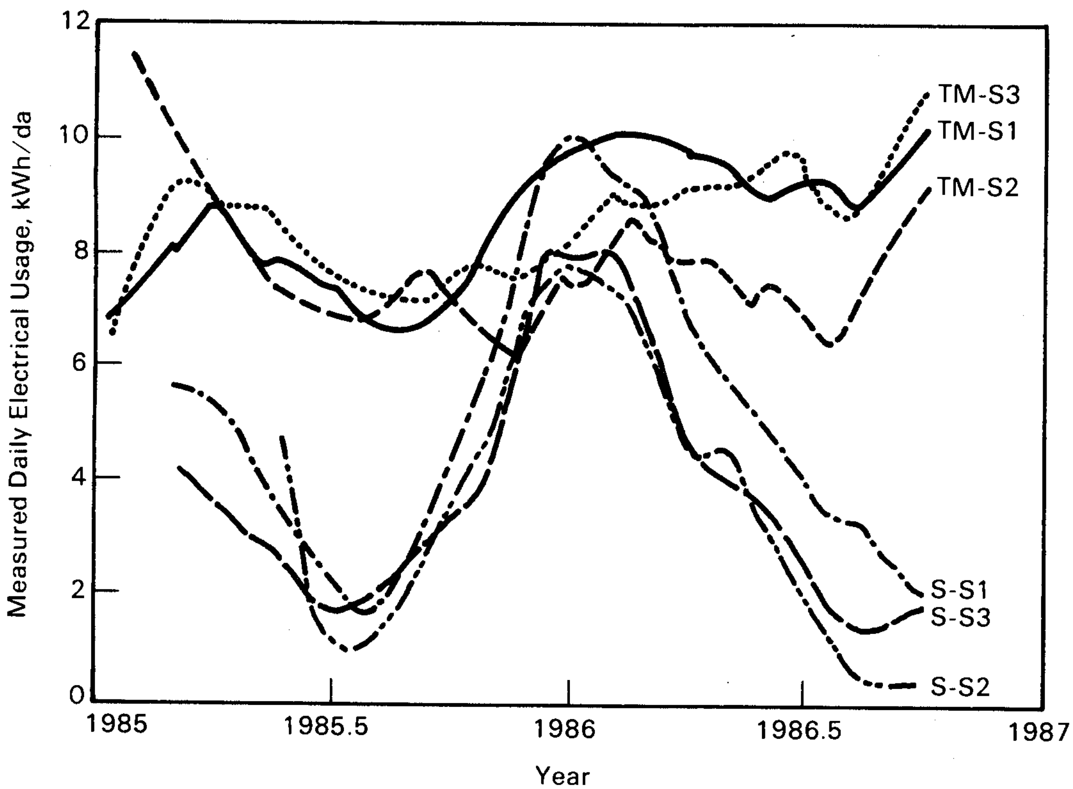

Figure 1. Comparison of ODOE solar (S) and conventional water heater (TM) typical daily electrical usage for solar zones 1, 2, and 3 (S1, S2, S3) and occupancy level 1/2.

since we expect electrical usage at solar sites to be negatively correlated with insolation; that is, highest usage in the winter, lowest in the summer, and intermediate in the spring and fall. What may be surprising is that the conventional water heater residences also show a strong seasonal pattern. The pattern is not as clearly associated with insolation - particularly in solar zone 2.

Because of the temporal dependency of water heater usage, annual electrical usage estimates should be based on an exact year's worth of data. Construction from any other time interval necessitates seasonal correction. There are so many uncontrolled factors in the present data set that such a seasonal correction on an individual residence basis would be very tenuous. A time frame that had sufficient residential response across data sets was July 19, 1985 to July 18, 1986.

A significant fraction of the individual residences in all of the data sets have a number of non-reporting usage days. The causes for non-reporting are primarily due to introduction of a new site into the data set after July 19, 1985 or departure of a site prior to July 18, 1986. There were also a relatively small number of reported equipment malfunctions.

To produce a value for annual electrical usage for water heater usage for residences with non-reporting days, those days of non-reported usage were estimated by utilizing the temporal dependence of residences with similar occupancy and geographic location and the residence's general relationship to the group value. This procedure allowed for the integrity of the site as well as seasonality of electrical usage to be incorporated into the estimate.

Linear regression analysis was used to estimate typical water heater energy usage as a function of solar/climate zone and occupancy level after adjustment for significant characteristics of individual residential units. The regression was performed on the logarithms of individual residential usage data. The motivation behind analysis of such transformed data is to make the variability of electrical usage for individual residences about any typical value constant. The consequence of the transformation is that terms in the typical usage model are percent effects as opposed to absolute effects. The regression model expressed the logarithm of an individual residence annual energy usage as the sum of typical usage for water heater type, plus solar/climate zone effect, plus occupancy level effect, plus cross product terms, plus covariate effects, plus an error term. The covariate effects considered were additional subsetting of occupancy levels 1 or 2; presence of dishwasher, flow restrictors, water heater wrap; location of water heater; income level and any teenagers in residence. For both the heat pump and solar water heater analysis, the Cp statistic (Mallows, 1973) was used to identify the most parsimonious model explanation of the structure in the data that can be accounted for with the full set of covariates.

For the data shown in Figure 2, the estimated typical savings for a large number of heat pump sites versus a large number of RSDP Triple Metered sites range from 435 kWh/yr for the 1/2 occupancy level to 1154 kWh/yr for the 3 occupant level. The standard errors for these savings are rather large; however, the estimates cited are significantly different from no savings at all. These savings are for retrofit heat pump systems; integral systems may have a different level of savings. Note that while each occupancy level is not distinct within a data set (i.e., occupancy levels 3, 4, and 5 overlap 2-sigma error bars), they are suggestive of a trend and are included for interest in the figure.

Solar Results

The regression model estimates provide multiplicative adjustment factors for comparing solar water heater electrical usage versus conventional water heater usage. ODOE solar usage is 45% less than corresponding conventional water heater usage across all three solar zones. The amount of savings is dependent upon solar zone: 32%, 42%, and 62% for solar zones 1, 2, and 3, respectively. It is interesting to note that energy usage for conventional sites are not distinguishable across solar zones. In short, the energy savings increase across solar zone is related to increased annual insolation.

The solar estimate comparison by solar zone and occupancy is presented in Figure 3. The estimates are adjusted for the significant covariates found (single person households, income level and presence of dishwashers, flow restrictors, and water heater wrap. Thus the estimates are placed on equal

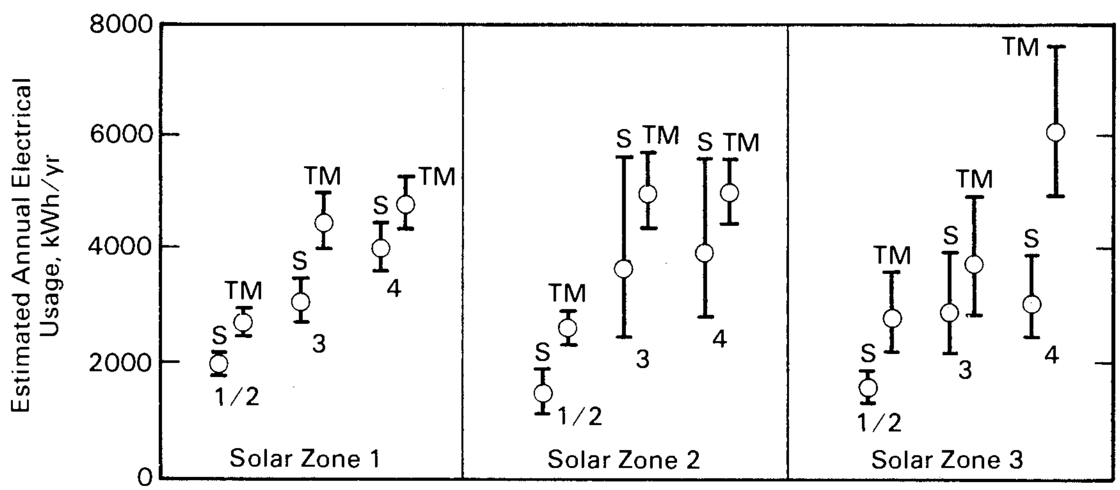

Figure 3. Solar comparison of estimated annual electrical usage (EAU) by occupancy level, solar zone and data set. Data sets include ODOE solar (S) and RSDP Triple Metered (TM). Occupancy levels within a residence include 1/2, 3, and 4.

Heat Pump Results

The regression model estimates provide multiplicative adjustment factors for comparing heat pump water heater electrical usage versus conventional water heater usage. Both estimated usage comparisons (ODOE heat pump versus Hood River and ODOE Heat Pump versus RSDP Triple Metered) were statistically significant. Heat pump electrical usage is 21% less than the RSDP Triple Metered conventional electrical usage and 35 % less than the Hood River conventional electrical usage.

The heat pump estimate comparison by occupancy is presented in Figure 2. The estimates are adjusted for the significant covariates found (single person households, presence of teenagers and dishwashers). Thus the estimated are placed on a equal fooling with each other so that summary statements on differences between occupancy levels and/or data sets can be easily made.

The significant covariate estimates associated with the heat pump analysis (the ODOE heat pump, Triple Metered and Hood River data sets) can be interpreted as follows: 1) one occupant uses 58% less electricity for hot water than two occupants; 2) when a child becomes a teenager in a residence, typically there is a 4% increase in usage for hot water; 3) a residence without a dishwasher typically uses 11% less electricity for hot water. Recall that the above interpretation is taken relative to the average of a large number of residential sites for both heat pump and conventional water heaters. Any given pairing of sites may provide a result in the opposite direction.

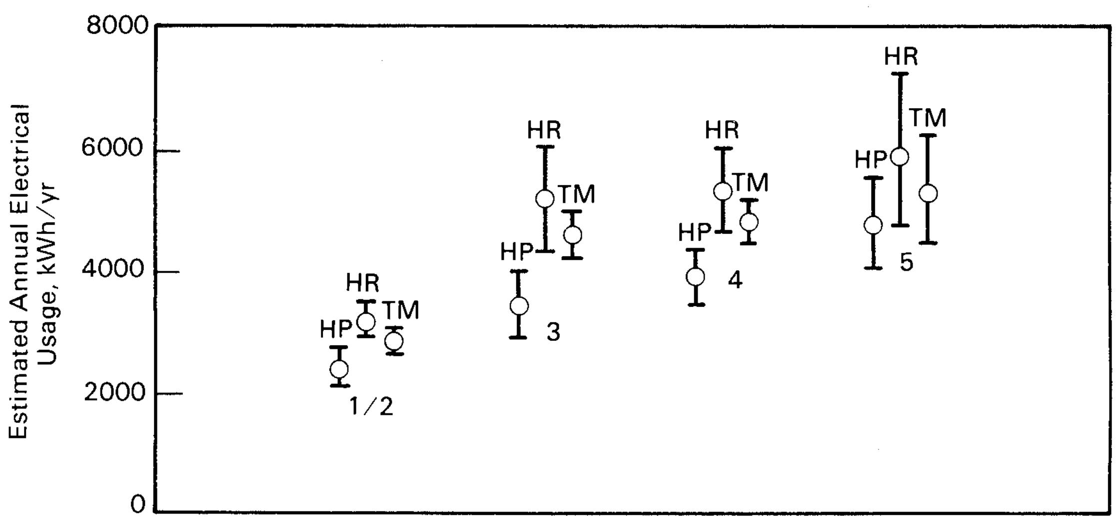

Figure 2. Heat pump comparison of estimated annual electrical usage (EAU) by occupancy and data set. Data sets include ODOE heat pump (HP), Hood River (HR), and RSDP Triple Metered (TM). Occupancy levels are 1/2, 3, 4, and 5.

footing with each other so that summary statements on differences between occupancy levels and/or water heater types can be made. Note that while each occupancy level is not distinct within a data set (i.e., occupancy levels 3 and 4 overlap 2-sigma error bars), they are suggestive of a trend and are included for interest in the figure.

The significant covariate estimates associated with the solar analysis can be interpreted as follows: 1) one occupant uses 60% less energy for hot water than two occupants; 2) a residence without a dishwasher typically uses 8% less electricity for hot water; 3) a wrap on the water heater typically reduces electrical usage by 8%; and 4) the use of flow restrictors decreases electrical usage by 8%. There was also an indication of a 5% increase in electrical usage corresponding to an increase in level of income. Recall that the above interpretation is taken relative to the average of a large number of residential sites for both solar and conventional water heaters. Any given pairing of sites may provide a result in the opposite direction.

For the data shown in Figure 3, the estimated typical savings for a large number of solar sites versus a large number of RSDP Triple Metered sites range from 727 kWh/yr for occupancy level 1 or 2 within solar zone 1 up to 3019 kWh/yr for occupancy level 4 within solar zone 3. The estimated savings for each solar zone and occupancy level considered is displayed in Table IV along with corresponding error estimates. Note that the error estimates are very high in solar zones 2 and 3 for occupancy levels 3 and 4. This is due to the reduced number of residences in those cells.

Table IV. Estimated electrical savings with solar water heaters (kWh/yr) (error estimated provided within parentheses).

	Solar Zone		
Occupancy Level	1	2	3
1/2	727 (158)	1145 (245)	1271 (386)
3	1375 (305)	1191 (860)	803 (684)
4	777 (320)	952 (744)	3019 (744)

The estimates for the individual solar zones generally agree with the load-fraction values presented in Table V. The load fraction is the theoretical percent of total energy for water heating that would be supplied by a particular solar water heating system. Table V shows the load fraction range for energy savings alongside the 95% confidence interval estimate of load fraction for each solar zone. The consistency is very strong.

Table V. Solar-load fraction comparison.

Solar Zone	Load Fraction Range	95% Load Fraction Confidence Interval
1	38 - 45	21 - 43
2	47 - 56	16 - 75
3	59 - 66	34 - 97

Conclusions

The analysis results presented here were derived from comparing estimated annual usage for heat pump and solar water heater residences (ODOE data set) with estimated annual usage for conventional water heater sites (RSDP Triple Metered and Hood River Conservation Project data sets).

Summary results for annual electrical usage estimates for heat pump and solar water heaters as well as conventional water heater usage are shown in Figure 4. The estimated annual usage appears lower for solar sites than for heat pump sites. The heat pump and solar sites use significantly less electricity than do conventional sites.

Comparison of mean estimated values show that heat pump water heaters use 21% (34%) less than their RSDP Triple Metered (Hood River) conventional counterparts. This corresponds to 825 kWh/yr (1307 kWh/yr).

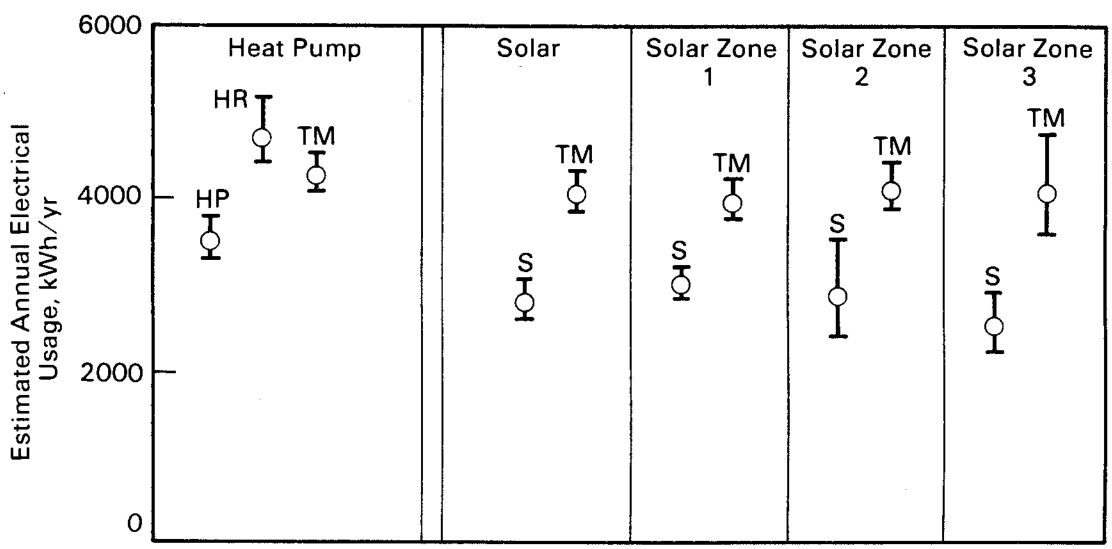

Figure 4. Estimated annual electrical usage estimates +/- 2 standard errors. Heat pump data are categorized as ODOE heat pump sites (HP), Hood River sites (HR), and RSDP Triple Metered sites (TM). The solar data are categorized as ODOE solar sites (S) and Triple Metered sites (TM).

Comparison of mean estimated values for the solar analysis reflect a savings dependent on solar zone. Savings of 31.9%, 42.3% and 62.4% (910 kWhr/yr, 1093 kWhr/yr, and 1723 kWhr/yr) are shown for solar zones 1, 2, and 3, respectively.

Interpretation of the estimated annual savings is relative to the average of a large number of sites for solar, heat pump and conventional water heaters. Any give pairing of specific sites may provide a result in the opposite direction.

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