Uncertainty Analysis of Life-Cycle Cost: Residential Electric Heat Pump Water Heaters

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This presentation demonstrates an explicit analysis of uncertainty when evaluating life-cycle cost of efficient technologies. The probability that more efficient technology will have lower life-cycle cost in a specific application is analyzed. Both life-cycle cost and payback period to consumers are calculated. Using residential water heaters as an example, we analyze distributions in place of single values for two sets of variables: equipment and consumers. For the equipment variables, uncertainties in the energy efficiency, price, and lifetime of heat pump water heaters are analyzed. For the consumers, variables include energy price and annual water usage. The uncertainty analysis provides additional information including:

- the probability that the efficient technology will have lower life-cycle cost, given the uncertainties;
- a distribution of life-cycle costs and payback periods for each efficient design;
- a relative ranking of the contribution of uncertainty in each input to the overall uncertainty in the life-cycle cost.

The determination of relative importance of contributions to the overall uncertainty serves to direct research toward: 1) reducing the uncertainty in the most important inputs; or 2) identifying the range of values (or subpopulation) that achieves reduced life-cycle cost relative to a less efficient technology.

Introduction

Typical residential electric water heaters produce heat using resistance coils. Heat pump water heaters obtain heat from the air near the water heater. Heat pump water heaters (HPWH) require less electricity than resistance water heaters (RWH) when providing the same quantity of heat to the water. The energy factor (EF) is about 0.86 for the RWH, and about 1.77 for the HPWH. (U.S. DOE 1993). This paper examines the difference in life-cycle cost between the typical electric resistance storage water heater and a heat pump water heater, under a wide range of input assumptions.

A purchaser must know several variables to make an informed choice between these two competing designs of electric water heaters. Key economic variables include: purchase price of the equipment and operating expense. Operating expense, in turn, is composed of electricity price, hot water usage, and equipment efficiency (accounting for draw schedule, ambient air temperature, inlet and outlet water temperature, standby losses, and recovery efficiency). When considering a population of households, as for a utility or government energy efficiency program, recognition must be given to the variation in operating conditions and consumer behavior among different households, which introduce uncertainty into the values assigned to these variables.

In this paper, subjective probability distributions are assigned to key variables, and a calculation of the life-cycle cost of the two competing designs is made. The difference in life-cycle cost between the RWH and the HPWH is a measure of cost-effectiveness of HPWH compared to the RWH. Simple payback period is also reported.

Life-cycle cost is used here to refer to the sum of purchase price plus discounted maintenance and operating expenses over the life of the product. Operating expenses include the cost of electricity and the cost of water.

The difference in life-cycle cost is calculated over a range of assumptions about the following variables: gallons of hot water used per day, incremental manufacturing cost of a heat pump water heater compared to a typical resistance water heater, lifetime of the water heaters, and efficiency of each design. In addition, the dependence of life-cycle cost upon assumptions about electricity price and discount rate are examined by sensitivity analysis.

Methodology

The general approach involves assigning a distribution of values to uncertain inputs. Then a sample is taken from each distribution (using the Monte Carlo method), and the resulting set of inputs is used to calculate life-cycle cost for each of the two designs (resistance and heat-pump). Results are tabulated in several forms: distribution of life-cycle costs for each design, given 1000 samples over the inputs; statistics on those distributions (various percentiles, mean, standard deviation); and the difference in life-cycle cost between resistance and heat pump designs.

Inputs

Two inputs are assigned discrete values: electricity price and discount rate. In a given utility service territory, the residential electricity rate is known. Three values (low, mid, and high) are used to illustrate the range among utilities in the U.S.A. Similarly, three values are assumed for discount rate, to test sensitivity to this assumption.

Four inputs are assigned distributions, to account for uncertainty: hot water usage, lifetime, incremental manufacturing cost of the heat pump water heater, and energy factor.

Hot Water Usage. Different households consume different quantities of hot water per day, depending upon such factors as ownership of hot-water-using appliances (e.g., clothes washers and dishwashers), number and age of occupants, occupancy patterns, and whether the cost of hot water is included in rent. (Thrasher 1990) The possible variation is assumed to be a normal distribution with mean 55 gallons hot water per day, and a standard deviation of 10 gal/day. (The range at three standard deviations is about 25 to 85 gallons per day.)

Operating expenses are the larger contribution (than equipment price) to life-cycle cost. When sampling within the distribution of values, higher hot water usage increases operating expenses, and lower hot water usage lowers operating expenses.

Lifetime of Water Heater. The lifetime of the water heater probably depends upon usage and water quality. Industry estimates of lifetime for residential electric water heaters are from 10 to 18 years (Appliance 1991). Here we assume a normal distribution for lifetime, with mean 10.1 years, and standard deviation 1.1 years, based upon statistical analysis of historical shipments and current saturation. (U. S. DOE 1993) (The range for plus or minus three standard deviations is about 7 to 13 years.)

A longer lifetime means a greater contribution of operating expenses to life-cycle cost. The assumption of a 10-year life is conservative; if heat pump water heaters have lower life-cycle cost under this assumption, they also have lower life-cycle cost at higher lifetimes.

Incrementa/ Manufacturing Cost. The manufacturing cost of the resistance water heater, and the incremental manufacturing cost (and its uncertainty) of the heat pump design, are taken from a recent U.S. Department of Energy Technical Support Document. (US DOE, 1993) The purchase price is taken from the same source, and only the uncertainty in the incremental manufacturing cost is assumed to contribute to uncertainty in the purchase price.

In other words, the uncertainty of markups has not been analyzed here. The purchase price can vary with volume of purchases, pricing strategies of competitors, rebate programs, current state of the economy (or of the financial condition of the retailer/distributor), etc. Such variation would increase the uncertainty in purchase price.

There is some evidence that our approach may overstate the life-cycle cost of heat pump water heaters, since the purchase price we assume is higher than that reported by EPRI for an actual model, more efficient than we assume here. (EPRI 1993)

Efficiency. Uncertainty in the efficiency of heat pump water heaters is arbitrarily treated as a normal distribution with standard deviation of 10% for the add-on heat pump (12.5% for heat pump plus R-25 insulation) based upon possible variation in design, as measured by laboratory test procedure.

The actual uncertainty in efficiency in the field will be larger, due to differences in inlet and outlet temperature, ambient air, and effects of draw schedule. These effects were not estimated here, but future research using simulation models is expected to help define the larger range of uncertainty.

Electricity Price. The price of residential electricity varies by geographic location (utility service territory), customer class, and (with some rate schedules) usage. Since each household faces a particular electricity price, this value is not treated as uncertain, but rather as a discrete value. Three values are used in the calculation to account for the variation across the U.S.A.: 4, 7.5, and

12.5 cents/kWh. The extreme values correspond roughly to lowest (Washington) and highest (New York) state prices, and the middle value corresponds to the national average. (EIA 1993a)

Note that all three values have been adjusted downward by about 10% from the average residential rate, to account for the observation (based upon analysis of RECS data (EIA 1993b)) that the average price of electricity for residential water heating is lower than the average price of total residential electricity. (USDOE 1993) The rationale for this observation is that electricity captures larger shares of the water heater market in locations where electricity prices are lower, and that some rate schedules provide discounts to customers having electric water heaters.

Higher electricity prices correspond to a greater contribution of operating expense to the life-cycle cost.

Discount Rate. We do not attempt to review here the arguments for selecting a particular value for the discount rate, when evaluating life-cycle cost. Instead, we selected three values for the discount rate: 2, 7, and 15% real.

Lower discount rate corresponds to a greater contribution of operating expense to the life-cycle cost.

Life-cycle Cost Calculation

The equations used to calculate life-cycle cost are shown in Table 1. Uncertain variables are characterized by normal distributions, shown in the table as "Normal (mean, standard deviation)."

A sample is drawn at random (using Monte Carlo sampling) from each of the distributions of the uncertain inputs, namely the first four inputs listed above. Using these values, and an assumed electricity price and discount rate, the life-cycle cost is calculated for each design (resistance or heat pump). This process of sampling from the distributions is repeated 1000 times.

Each time, the difference in life-cycle cost is calculated (heat pump minus resistance). Negative values for this difference occur when the heat pump life-cycle cost is lower than the resistance life-cycle cost; positive values occur for the difference when the heat pump life-cycle cost is higher than the resistance life-cycle cost.

In all, the difference in life-cycle cost is calculated 9,000 times for each of the design options (1000 samples over the distributions of the uncertain variables times 3 electricity prices times 3 discount rates).

Results

Explicitly accounting for the uncertainty in 4 key variables, and variation in 2 others, shows that in most cases, the heat pump water heater has a lower life-cycle cost. Figure 1 shows the life-cycle costs for three electric water heater designs: resistance, add-on heat pump, and add-on heat pump plus R-25 insulation. The mean life-cycle cost is lower for the heat pump designs than for the resistance water heater.

Equally important, the range of values for the life-cycle cost is reduced for the heat pump water heater, compared to resistance. Once purchased, uncertainty in future water usage or electricity price lead to a lower absolute variation in operating expense, owing to the lower operating expense of the heat pump water heater compared to resistance.

Table 2 shows, for the case of 7 cents/kWh discounted at 7%, the median life-cycle cost of the resistance water heater is $2829, compared to $1966 for the heat pump. The standard deviation for the resistance unit is $564, compared to $324 for the heat pump unit. The uncertainties in four inputs lead to a 50% probability that the LCC will be between $2474 and $3223 for the resistance unit, compared to $1765 to $2188 for the heat pump unit.

Probability That Heat Pump Water Heaters Have Lower Life-Cycle Cost

Figure 2.A shows the cumulative probability distribution of life-cycle cost differences, assuming an electricity price of 7.5 cents/kWh, and a discount rate of 7%. All values are negative, meaning that the life-cycle cost is lower for the heat pump than for the resistance design.

Figure 2. B shows the cumulative probability distribution of life-cycle cost differences, assuming 4 cents/kWh and 15% discount rate. The heat pump has a lower life-cycle cost than the resistance unit for 77% of the sample.

Table 3 summarizes the cumulative probability distributions of life-cycle cost differences under all the assumptions for discount rate and electricity price. For each of these scenarios, the probability that the heat pump will have lower life-cycle cost is high, ranging from 77 to 100%.

Heat pump water heaters are found to have higher life-cycle costs when the discount rate is high (15%) and when electricity price is low ($0.04/kWh).

Table 1. Life-Cycle Cost of Electric Storage Water Heater

LCC = PC + WC + EC	* Total life-cycle cost
PWF = 1/R * [1 - (1 + R) ^ (-Year)]	* Present worth factor
R = { 2%, 7%, 15% }	* Discount rate
Year = Normal (10.1, 1.1)	* Lifetime
PC = IC + Markup * [MC(a) + IMC]	* Purchase cost
IC = { 126.12, 226.12, 248.65 }	* Installation cost for { a, b, c }
Markup = { 1.552, 1.374, 1.368 }	* Markup for { a, b, c }
MC (a) = 89.68	* Baseline manufacturing cost
IMC (a) = 0	* Incremental manufacturing cost for a
IMC (b) = Normal (201.82, 10.015)	* Incremental manufacturing cost for b
IMC (c) = Normal (201.83, 10.240)	* Incremental manufacturing cost for c
WC = V * ($/gal) * 365 * PWF	* Water cost
V = Normal (55, 10)	* Daily water consumption in gallon
$/gal = $0.002	* Water price per gallon
EC = ($/kwh) * (kwh/yr) * PWF	* Electricity cost
$/kwh = { $0.04, $0.075, $0.125 }	* Electricity price
kwh/yr = [Qwd1 + Qloss] / RE*365 / 1000	* Annual electricity consumption
Qwd0 = 64.3 * 8.35 / 3.412 * 77	* Heat demand determined by 64.3
Qwd1 = V * 8.35 / 3.412 * 77	* Heat demand determined by V=N(55, 10)
Qloss(a) = Qwd0 * (0.98/0.86 - 1)	* System heat loss for a
Qloss(b) = Qwd0 * (0.98/0.90 - 1)	* System heat loss for b
Qloss(c) = Qwd0 * (0.98/0.93 - 1)	* System heat loss for c
RE = (Qloss +Qwd1) / Qwd1 * EF	
EF (a) = Qwd0 * 365 / 1000 / 5096.2	* kwh/yr for efficiency of a
EF (b) = Qwd0 * 365 / 1000 / Normal (2479.3, 242)	* kwh/yr for efficiency of b
EF (c) = Qwd0 * 365 / 1000 / Normal (2316.7, 293)	* kwh/yr for efficiency of c

Note: a - Baseline unit; b - Add-on heat pump unit; c - R-25 insulation unit

Simple Payback Period

Table 4 shows the distribution of payback for the heat pump designs, compared to a resistance water heater, for different electricity price assumptions. At 7.5 cents/kWh, the add-on heat pump has a mean payback of 2.2 years. The right side of Table 4 shows the probability that payback is lower than 1, 3, 5, or 10.1 years. For electricity price at or above 7.5 cents/kWh, nearly 100% of the sample have payback under 5 years. For electricity price at 12.5 cents/kWh, nearly 100% have payback under 3 years. For electricity price at 4 cents/kWh, only 6% have payback at or below 3 years, but about 80% have payback at or below 5 years.

Distributions Can Be Misleading

A visual comparison of the uncertainty in life-cycle costs for the two designs does not provide a meaningful comparison of the life-cycle cost of one design compared to another. Figure 3 shows the distribution of life-cycle costs obtained for the two designs, given the uncertainties in the inputs. While there is significant overlap between the distributions, this masks the fact that there is a correspondence between each point on the distribution for one design and a point on the distribution for the other design. These matched pairs have some input values in common, for example, gallons of hot water per day, and lifetime. Accounting for these values in common is accomplished

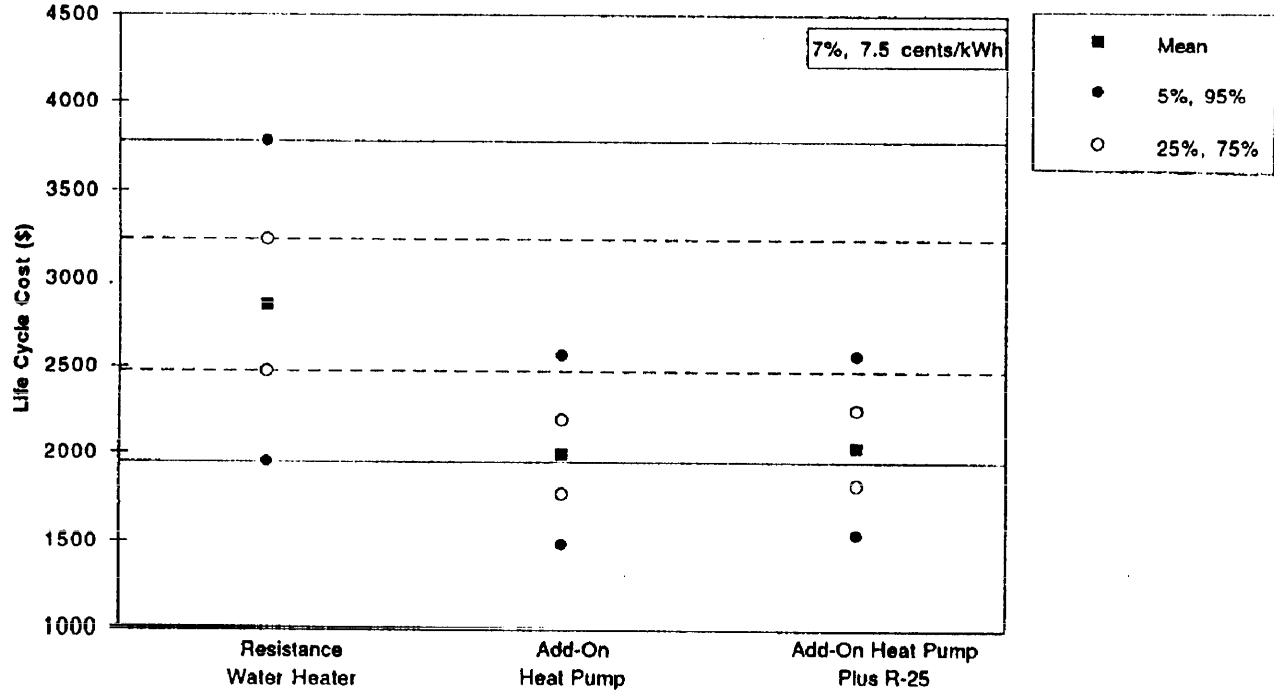

Figure 1. Life-Cycle Costs with Uncertainty

Table 2. Statistics of Life-Cycle Cost ($) Distribution of Three Water Heater Designs

	Baseline	Add-on Heat Pump	Heat Pump + R-25
Minimum	1197	1086	1115
Median	2829	1966	2014
Mean	2854	1991	2030
Maximum	5052	3160	3228
Standard deviation	564	324	320
5% percentiles	1947	1481	11537
25% percentiles	2474	1765	1813
50% percentiles	2829	1966	2014
75% percentiles	3223	2188	2245
95% percentiles	3776	2567	2563

Note: Discount rate - 7%; Electricity price - 7.5 cents/kWh

by calculating the difference in life-cycle cost between the two designs, as described above.

Relative Importance of Input Uncertainties

The relative contribution of the uncertainty in each input variable to the total uncertainty, called the "importance," was calculated. This is the rank correlation of the uncertainty of each input with the total uncertainty. Results are presented in Table 5.

Among the uncertainties analyzed, the most important was gallons per day of hot water usage, followed by energy factor and lifetime. Considering the variation in possible designs of heat pump water heaters (add-on heat pumps, integral heat pumps, and different efficiencies) and variations in efficiency for specific applications (due to climate, location of heat pump, and draw schedule) would probably increase the importance of the energy factor uncertainty.

Significantly less important was uncertainty in incremental manufacturing cost. Including variation in retail price would probably increase the importance of equipment price (combining incremental manufacturing cost and retail price uncertainties).

This methodology for comparing relative importance of the uncertainties can be useful for focussing future research on those uncertainties which are most important, and for identifying those uncertainties which do not affect the conclusions.

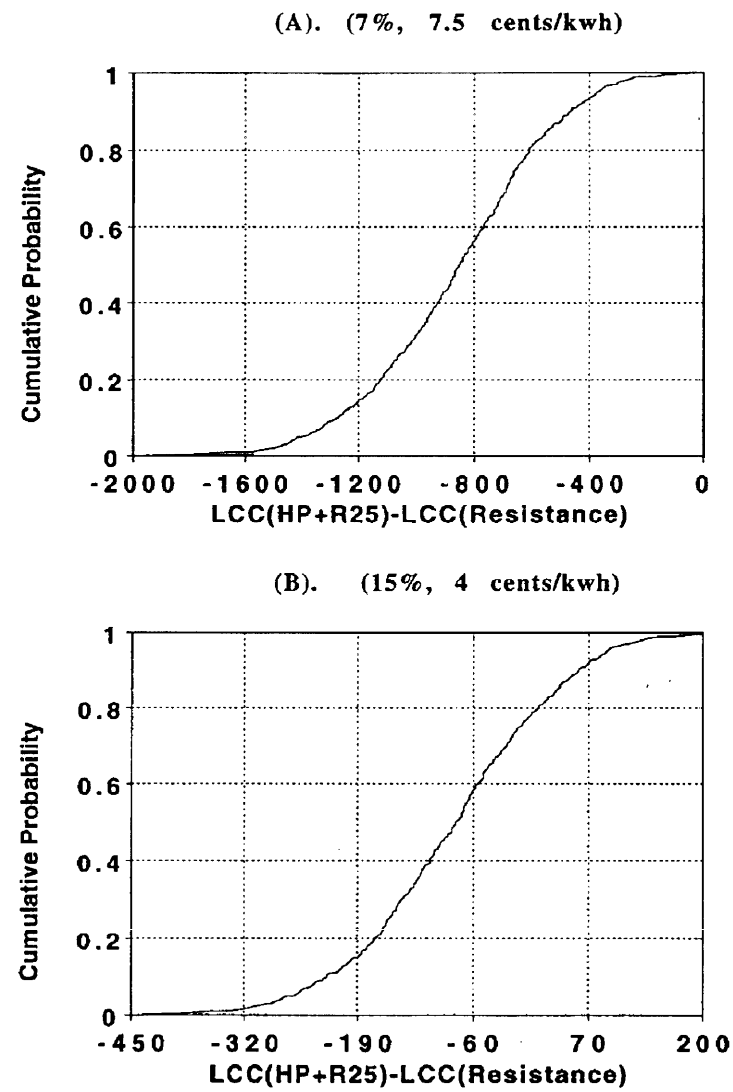

Figure 2. Cumulative Distribution Function of LCC Difference

Limitations

This paper is an example of an uncertainty analysis, demonstrating an approach to analyzing life-cycle cost of energy efficient products, given uncertainties in several variables. Additional research is needed to explore the full range of uncertainties.

Uncertainties in the following variables were not examined: wholesale and retail markups (ratio of price to cost), maintenance cost, price of water. The relationship between efficiency and water consumption is complicated for water heaters, and no simulation was conducted to account for the effect on efficiency due to such factors as: differences in draw schedule, inlet and outlet water temperatures, and ambient air temperature.

Non-economic factors, such as noise or mechanical complexity, which may also influence consumer acceptance of heat pump water heaters, were not considered.

Conclusions

Explicit consideration of some of the key uncertainties affecting the costs of heat pump, compared to resistance, residential water heaters yields an indication of the likelihood that the more efficient, and more expensive. heat pump units will have lower life-cycle cost to consumers. In all scenarios examined, the probability is high that heat pump water heaters will have lower life-cycle costs than resistance water heaters.

Table 3. Minimum and Maximum Difference in LCC, and Probability that Heat Pump has Lower LCC

Electricity Price (cent/kWh)	Discount Rate	*LCC (HP) - LCC (R)* *MIN ($)*	*MAX ($)*	Probability of Lower LCC (HP)
4	15%	-485	232	77.5%
4	7%	-1127	171	95.8%
4	2%	-1263	70	99.2%
7.5	15%	-1178	108	99.3%
7.5	7%	-1758	-84	100.0%
7.5	2%	-2674	-128	100.0%
12.5	15%	-2614	-69	100.0%
12.5	7%	-4359	-303	100.0%
12.5	2%	-5272	-443	100.0%

Note: LCC (HP) is life-cycle cost of heat pump water heater.
LCC (R) is life-cycle cost of resistance water heater.

Table 4. Analysis of Payback Period

Electricity (cent/kWh)	Model	Low	Mean	High	Probability With Payback Years <=1	<=3	<=5	<=10.1
4	Add-on	2.1	4.3	6.5	0%	6.0%	81.3%	99.78%
	R-25	2.0	4.4	6.8	0%	6.6%	76.7%	99.83%
7.5	Add-on	1.1	2.3	3.5	0%	89.3%	99.6%	100%
	R-25	1.1	2.3	3.5	0%	88.4%	99.5%	100%
12.5	Add-on	0.7	1.4	2.1	11.0%	99.6%	100%	100%
	R-25	0.7	1.4	2.2	8.4%	99.5%	100%	100%

Note: Low and High values are the Mean values +/- two standard deviations.

Uncertainties were assigned to four key variables: gallons of hot water used per day, lifetime, incremental manufacturing cost of heat pump (over resistance) designs, and efficiencies of the heat pump design. In addition, the analysis was repeated for three electricity prices, and three discount rates, for a total of nine scenarios.

The relative contribution to the overall uncertainty in life-cycle cost due to the uncertainty in each of the input variables was calculated. The greatest contribution to overall uncertainty came from hot water usage (gallons per day), followed by lifetime and energy factor. A smaller contribution came from uncertainty in incremental manufacturing cost of the heat pump water heater.

Some uncertain variables important for actual energy consumption in the field were not analyzed, including the temperature difference between inlet and outlet water, ambient air temperature, and differences in draw schedules.

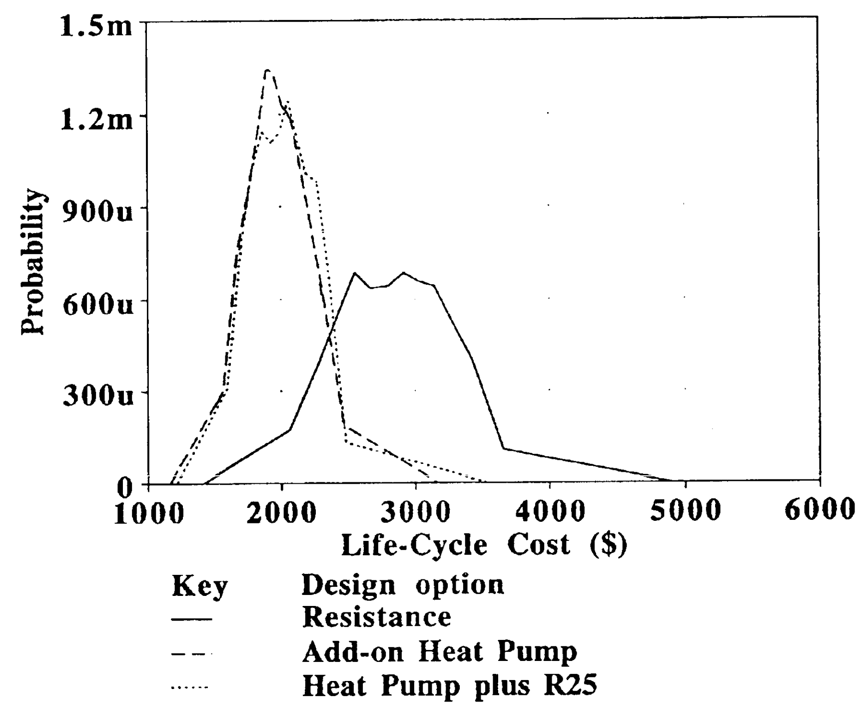

Figure 3. Distribution of Water Heater LCC due to Uncertainty (7%, 7.5 cents/kwh)

Table 5. Rank Correlation ("Importance") of Uncertainty in Inputs to Uncertainty in Life-Cycle Cost

Design:	Resistance	Add-on Heat Pump	Heat Pump +R25
Input:			
Daily water use	0.931	0.875	0.838
Lifetime	0.335	0.327	0.316
Energy factor	0	-0.357	-0.369
Incremental manufacturing cost	0	0.017	0.012

The methodology demonstrated here can help identify those uncertainties which are most important to the life-cycle cost of an energy efficient technology, relative to a common, less-efficient design. The determination of relative importance of the uncertainties in inputs can guide future research efforts.

Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Office of Codes and Standards, of the U.S. Department of Energy under Contract No. DE-AC0376F00098. The opinions expressed in this paper are solely those of the authors and do not necessarily represent those of the Department of Energy or of Lawrence Berkeley Laboratory.

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