RESIDENTIAL WATER HEATING: WHAT'S BEST FOR YOU?*

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INTRODUCTION

The domestic water heater is one of the largest energy consumers in the residential home. In 1975, electric water heaters were estimated to have consumed 84 × 10^9 kWh and gas-fired water heaters are estimated to have consumed 1.0 PJ (0.95 GBtu) of energy.[1] Today there are several alternative water heating methods from which a consumer can choose. These methods are electric resistance, natural gas, heat pump water heater (HPWH), desuperheater system, and solar. The purpose of this paper is to compare the efficiencies and economics of these water heating alternatives.

THE STUDY METHODS

The space heating, space cooling, and conventional water heating requirements of a 167 m^2 (1800 ft^2) well-insulated house were calculated for 115 U.S. cities using average weather years. (A complete description of the house and its space heating, cooling, water heating, and internal loads is contained in Ref. 2.) The home was assumed to be cooled to 25.5°C (78 F) during the summer by air conditioning, and heated to 21°C (70 F) during the winter by either an air-to-air heat pump or electric resistance space heaters. It was assumed that the water storage tank is located within the thermal envelope* and that the occupants consumed 0.256 m^3 (70 gal) of 49°C (120 F) water each day. The water heating energy was calculated based on the assumptions that the feed line to the hot water tank is from an underground pipe and that the feed water is in thermal equilibrium with its earth surroundings. The underground water supply line is assumed to be at a depth just below the frost line or at 0.5 m (1.5 ft), whichever is greater.

It is usually assumed that water heating is accomplished with little or no influence upon either space heating or cooling needs of a house. This is not a valid assumption in most homes. In a well-insulated home, losses from the water heater shell influence the home's heating and cooling needs, if the storage tank is within the thermal envelope. Two of the alternate water heating methods, the HPWH and the desuperheater system, interact to even a greater degree with the home's heating and cooling needs because the systems use pumped energy which must be supplied by the heating and cooling system. Energy is removed from the thermal envelope of the house and is transferred through the heating system, affecting energy consumption of the space-conditioning system. For the purposes of this study, the interactive impact of alternative water heating systems on the space-conditioning energy consumption has been assigned to the water heating process even though the differential energy might actually be consumed by the space heating or cooling system.

Since each home's water heating requirements are different, it is best to evaluate each system's performance in relative terms. The alternative all-electric systems can easily be compared through use of an effective annual water heating coefficient of performance (COP). "Effective COP" as used in this paper refers to the ratio of energy consumed by an electric

*It is assumed that all space within the thermal envelope is conditioned space.

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resistance system supplying a given amount of hot water to the energy consumed (directly and indirectly through the space-conditioning system) by an alternate water heating method supplying the same service. The conventional electric resistance system, used as the basis of comparison in this study, is assumed to demonstrate a water heating COP of 1.0 in all locations, considering normal losses.

Effective water heating performances have been calculated for several cities in the continental United States through the use of a computer model. The alternatives evaluated are: (1) electric resistance water heater; (2) heat pump desuperheater water heating system with electric resistance auxiliary; and (3) HPWH in an electrically resistance heated and air-conditioned house and in a heat pump space-conditioned house. Additionally, the consumption of an equivalent gas water heating system was estimated for several of the cities so that relative economics could be developed.

The assumptions used in this simulation do not consider complicating factors such as heat exchanger fouling in either the desuperheater system or the HPWH system. This very real problem could be expected to reduce energy savings and increase maintenance costs.

DESUPERHEATER WATER HEATING

Many homes are heated and cooled with an air-to-air heat pump. Most of these homes heat water with an electric resistance water heater. The homeowner employing this combination is purchasing electrical energy for both space conditioning and water heating. By adding a desuperheater heat exchanger and water circulation pump to the existing air-to-air heat pump, the homeowner can save large quantities of energy.

Domestic hot water, at temperatures between 49°C (120 F) and 60°C (140 F), can be produced using the high-temperature energy in the refrigerant circuit of the heat pump. An analysis of the refrigerant cycle of a modern heat pump shows that between 11% and 18% of the total pumped energy is available for this purpose. In this study, we have assumed that 15% of the pumped energy can be used for producing domestic hot water. During the heating season, the additional energy needed for water heating is delivered by the heat pump at the seasonal performance factor (SPF) of space heating. During the cooling season, some or all of the water heating energy is available as a by-product of the cooling process; one only has to transfer the energy from the cooling system to the water storage tank. The desuperheater system generally requires a water pump to circulate water between the heat exchanger and the storage tank. During the cooling season the electric power consumption of this pump amounts to about 5% of the heat energy delivered to the storage tank. During months which do not require either heating or cooling, water is heated by electrical resistance units.

Figure 1 shows the arrangement of the primary components of an air-to-air heat pump and desuperheater water heating system. The air-to-air heat pump performance characteristics used for this analysis are typical of a high-quality modern heat pump demonstrating a 2.75 steady-state heating COP at 8.3°C (47 F). The 0.310 m^3 (82 gal) hot water tank selected for the desuperheater system is larger than tanks conventionally used to compensate for the longer temperature recovery time for this system (as compared to electric resistance water heating systems). The larger tank is necessary to assure hot water will be available and delivered at maximum efficiency. Heat pumps with desuperheaters are available today from several major heat pump manufacturers.

HEAT PUMP WATER HEATERS

The HPWH has recently become available to the consumer and is an effective energy conserving device. A national laboratory is supporting the development and demonstration of one of these devices as well as experimentally evaluating its performance. Experimental investigations have shown this unit, operating in a 20°C (68 F) environment, to provide 49°C (120 F) water at a COP of 2.15. This value has been used in making the interactive heat pump water heater calculations in this study.[3]

The effective performance of the HPWH system is dependent upon its actual physical location (either inside or outside the thermal envelope) and the type of HVAC system with which it is being teamed, as well as its efficiency. Therefore, the system's operating conditions must be specified. The HPWH requires air temperatures above about 7°C (45 F) to operate effectively. In northern cities, the water heater needs to be located in a relatively warm area. In southern cities, the space-cooling supplied by the water heater can be effectively used by locating the system within the thermal envelope. In this study, all calculations have been made assuming that this system was within the thermal envelope of the house. A detailed description of the HPWH is beyond the scope of this study but can be obtained from Ref 4.

HEAT PUMP WATER HEATING EFFECTIVENESS

A HPWH which is located within the thermal envelope can be used with all space heating alternatives; only two of the most common methods are discussed here. The HPWH located within the thermal envelope has both beneficial and detrimental influences on a house space-conditioning system. In the summer it produces useful space cooling while water is being heated, but during the winter, all pumped heat must first be passed through the heating plant at its efficiency. The net effect of both of these factors is reflected in the effective water heating COP. The HPWH within the thermal envelope significantly affects both heating and cooling loads.

Heat Pump Water Heater in an Air-to-Air Heat Pump Heated House

The effective water heating COP allows one to compare the actual costs of water heating although the energy is purchased for two different systems within the house. The effective water heating COPs for the HPWH/air-to-air heat pump system are shown in Fig. 4. This figure indicates that water heating efficiency is strongly influenced by the heating and cooling requirements of the house. The effective COPs are much higher in the South than in the North.

The effective COPs of the desuperheater system and the heat pump water heater system in the air-to-air heat pumped house are similar for much of the country.

Heat Pump Water Heater in an Electrically Heated and Air Conditioned House

A HPWH heater within the thermal envelope of the house can contribute significantly toward reducing cooling requirements, but it significantly increases space heating requirements because all water heating requirements are supplied as purchased energies either at the house heating plant or water heater.

Figure 5 shows that effective water heating COPs approach unity in northern cities. In the South, effective use of two outputs is being made since the HPWH contributes an important air-conditioning function. In the North, the cooling is not needed as much and effective water heating COPs approach 1, indicating that the majority of water heating energy is purchased energy. If a HPWH is located in an area which is always above 7°C (45 F), but heated by waste heat, the effective water heating COPs will be approximately 2.15.

COMPARATIVE ECONOMICS

One concern to the consumer is (or should be) the actual cost of owning and operating each of the alternative systems during its lifetime. Life cycle cost analysis allows one to determine the present-day dollars that could purchase and operate a system for the expected lifetime. For this analysis, the useful life of water heaters is assumed to be 10 years. The economic scenario used in this study uses 1979 electrical rates and assumes that electricity will not escalate in real terms (0%/yr), that natural gas will escalate at a rate of 2.27%/yr, and that the individual's personal discount rate is 2%/yr in real terms. This personal real discount rate indicates that the individual has available alternative investment opportunities yielding 2%/yr in real terms. These assumptions yield present worth factors* of 8.892 and 10.135 for electric and gas systems respectively, assuming a 10-year life cycle. The first cost of each system consists of equipment and installation costs. The installation costs assumed were $50 for the gas, electric, and heat pump water heaters; and $100 for the desuperheater system. No maintenance costs have been included in the analysis. Equipment costs used are those prices available to the retail consumer.

System first costs, effective annual energy consumption and life-cycle costs of five water heating and space-conditioning system alternatives in three cities with quite different climates, are shown in Tab. 1. The total life-cycle cost is the estimated value in today's dollars that the homeowner needs to commit to purchase and prepay all fuel costs for the 10-year life cycle. Each city's actual fuel prices in 1979 have been used in calculating the fuel present worth.[6] The homeowner whose home is heated and cooled by an air-to-air heat pump can elect to heat water by three electrically powered alternatives or by natural gas if available. Figure 6 shows a comparison of the electrically powered choices available to this person. In

*The present worth factor is the multiplier used with a constant fuel consumption rate to simplify computation of the sum of the time series of payments over a system's life in constant dollars.

Minneapolis, there is a 12% spread in life-cycle costs for the all-electric systems, while heating water with natural gas costs about 52% of electric resistance water heating. In Knoxville and Tampa, the life-cycle cost of heating water with natural gas is 81% and 61% respectively of the cost of electric resistance water heating. Natural gas water heating is the most economical method in all three cities.

Solar water heating methods have not been evaluated in this study, but an independent laboratory recently tested four systems.[7] Reference 7 indicates that solar water heaters could be expected to demonstrate effective water heating COPs of about 2 to 4. System costs are reported to be in the range of $1,300 to $3,000.

CONCLUSIONS

Today's residential consumer can select water heating options which result in large electrical energy savings. The homeowner using a desuperheater water heater system should expect effective annual water heating COPs which range from 1.3 for northern cities to 2.9 in southern cities. The average consumer could expect to save between 800 and 2500 kWh/yr with a desuperheater if he is presently heating water with a conventional electric water heater. A HPWH within the thermal envelope of an air-to-air heat pumped home would yield similar savings.

Even though the consumer can achieve significant energy savings, these savings may not translate into significantly different life cycle economics. The major economic conclusions of this study are:

1. The desuperheater water heater can save a significant amount of energy at attractive life-cycle costs and acceptable first costs if the owner is choosing between electrically powered alternatives.

2. The HPWH located within the thermal envelope of the air-to-air heat pump heated house offers slightly better life-cycle costs than does the desuperheater system.

3. Water heating with natural gas offers the most favorable life-cycle costs of all alternatives considered in this study and is nearly the lowest first-cost system.

4. Installation of a HPWH within the thermal envelope of an all-electric home may or may not offer a favorable life-cycle alternative, depending in large part upon how much air conditioning is normally done in that house.

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TABLE 1. Performance and economics of water heating alternatives[a]

	Water heating system				
	Gas	Electric	Heat pump system located in: electrically heated & air conditioned house	Heat pump system located in: a/a heat pump heated house	Desuperheater
First cost[b]	$260	$250	$800	$800	$790
Minneapolis, Minnesota - 0.0492 $/kWh					
Effective annual fuel consumption	30.15 mcf	5654 kWh	4169 kWh	3643 kWh	3969 kWh
Effective annual fuel cost	$116.68	$278.17	$205.11	$179.23	$195.27
Fuel present worth	$1182.55	$2498.52	$1842.30	$1609.84	$1753.91
System life cycle present worth	$1442.55	$2748.52	$2642.30	$2409.84	$2443.91
Knoxville, Tennessee - 0.0304 $/kWh					
Effective annual fuel consumption	25.07 mcf	4702 kWh	3075 kWh	2413 kWh	2938 kWh
Effective annual fuel cost	$97.02	$142.94	$93.48	$73.35	$89.31
Fuel present worth	$983.30	$1283.88	$839.63	$658.82	$802.18
System life cycle present worth	$1243.30	$1533.88	$1639.63	$1458.82	$1592.18
Tampa, Florida - 0.0434 $/kWh					
Effective annual fuel consumption	19.90 mcf	3732 kWh	1091 kWh	882 kWh	1280 kWh
Effective annual fuel cost	$77.02	$161.97	$47.35	$38.28	$66.55
Fuel present worth	$780.60	$1454.81	$425.29	$343.83	$498.95
System life cycle present worth	$1040.60	$1704.81	$1225.29	$1143.83	$1268.95

[a]Assumes 10-year life cycle, actual city electrical costs, $3.84/mcf gas costs, economic scenario 0% real electrical cost escalation, 2.27% real gas cost escalation, and 2% discount rate, resulting in an 8.892 present worth factor for electrical systems and a 10.135 present worth factor for gas systems. Hot water consumption is 0.265 m^3/day (70 gal/day) in all cities.

[b]Purchase price installation costs using retail equipment prices.

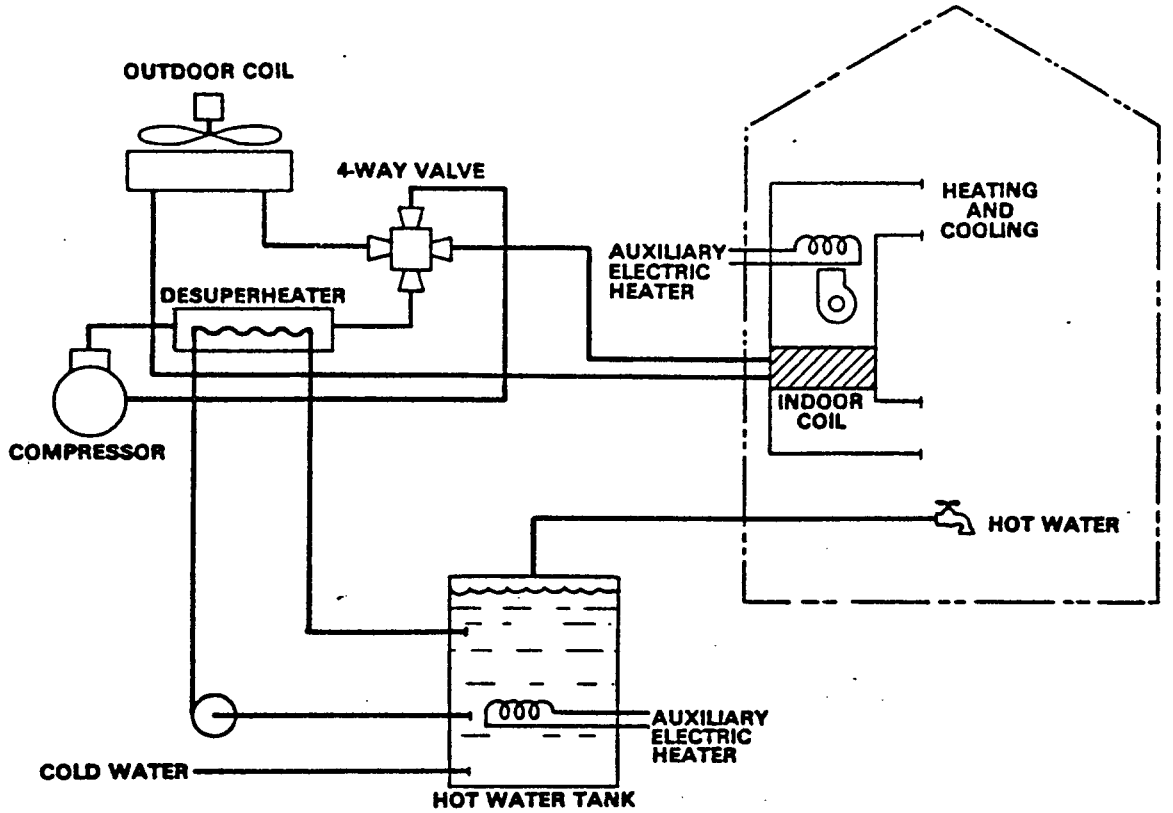

Figure 1. Simplified schematic of an air-to-air heat pump with desuperheater hot water

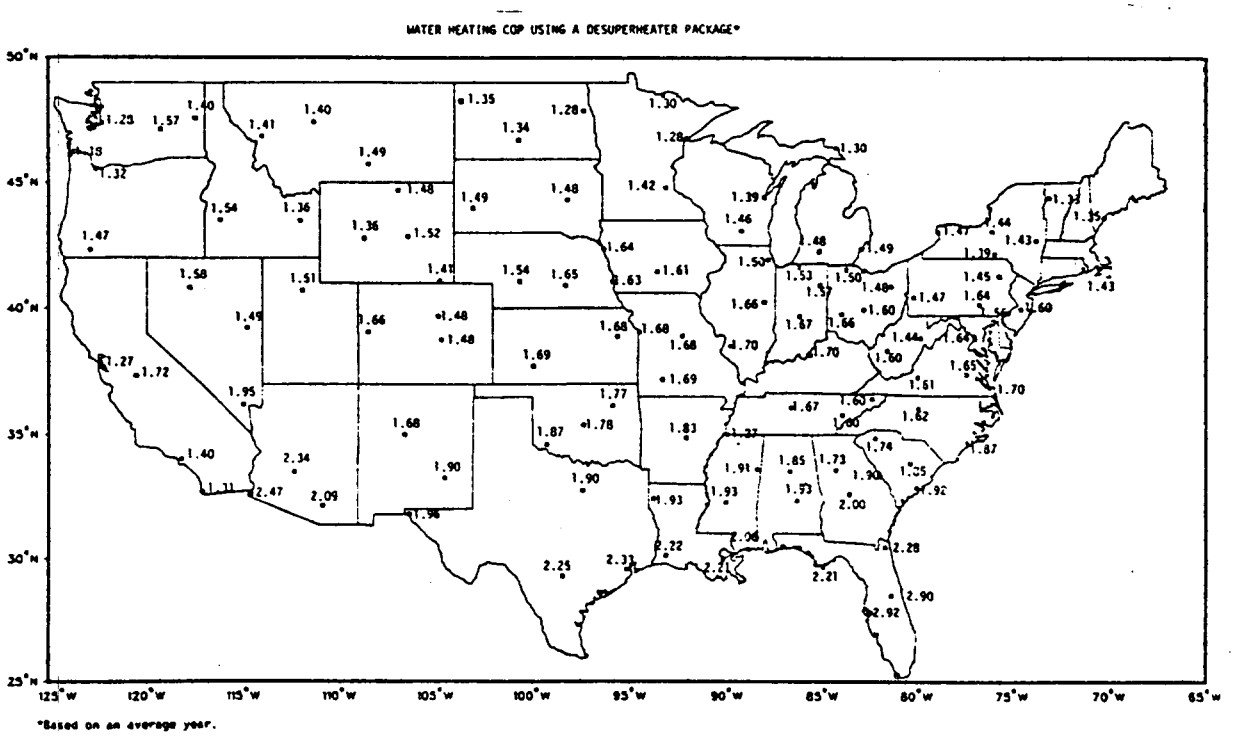

Figure 2. Effective water heating COP using a desuperheater package (based on an average year)

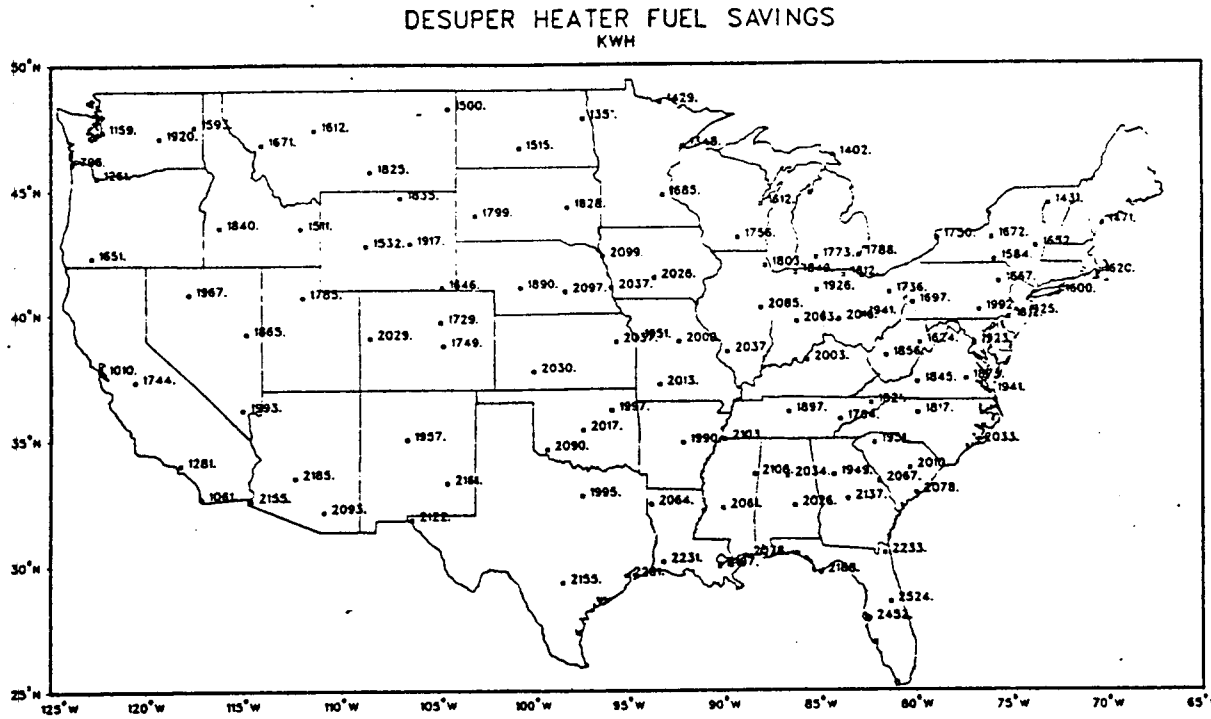

Figure 3. Desuperheater power savings (kWh) with respect to electric water heating

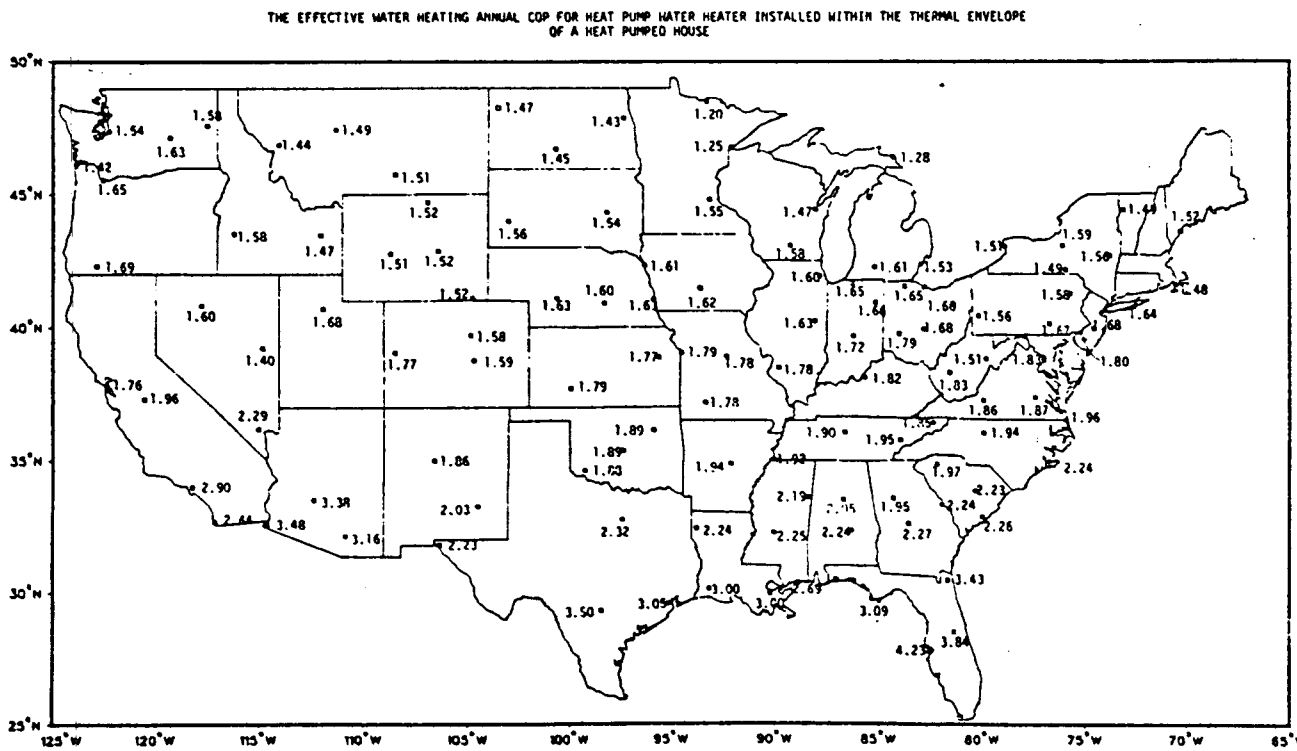

Figure 4. The effective water heating annual COP for a HPWH installed within the thermal envelope of a heat pumped house

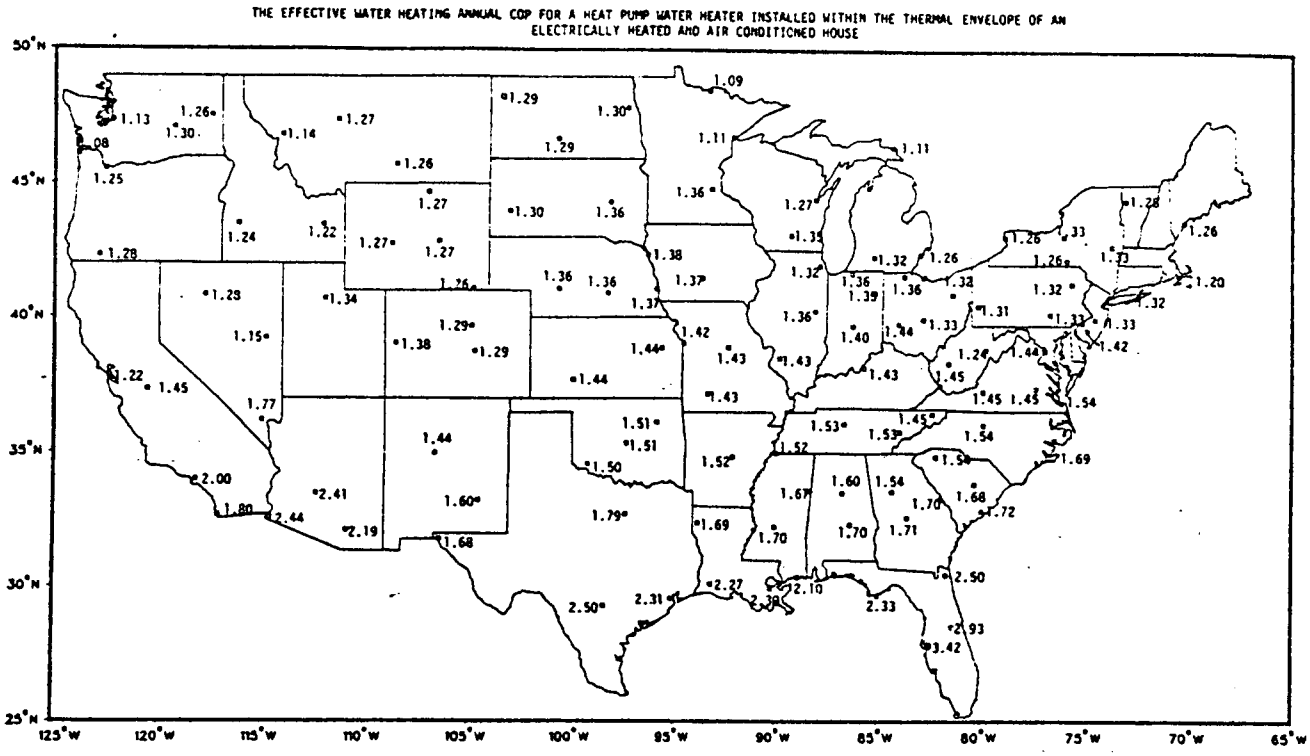

Figure 5. The effective water heating annual COP for a HPWH installed within the thermal envelope of an electrically heated and air conditioned house

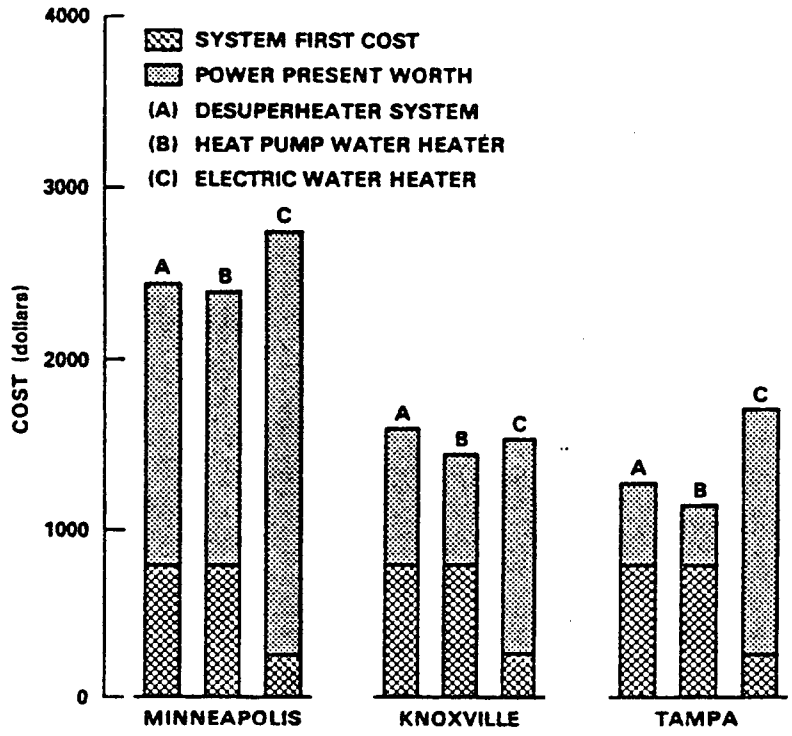

Figure 6. Water heating life cycle costs in an all electric air-to-air heat pumped house