Applications of Commercial Heat Pump Water Heaters in Hot, Humid Climates

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ABSTRACT

Heat pump water heaters can provide high-efficiency water heating and supplemental space cooling and dehumidification in commercial buildings throughout the United States. They are particularly attractive in hot, humid areas where cooling loads are high and the cooling season is long. Because commercial kitchens and laundry facilities have simultaneous water heating and cooling needs, they are excellent applications for heat pump water heaters.

Typical heat pump water heaters (HPWHs) operate at an annual coefficient of performance (COP) of approximately 3.0 for water heating alone. Space conditioning benefits of about 0.67 Btu are delivered at no additional cost for each Btu of water heating output. In situations in which this cooling output is valued, the dual thermal outputs for heating and cooling make heat pump water heaters particularly attractive. The comfort value of added cooling in overheated facilities and the resulting increase in employee and customer satisfaction are frequently cited as additional benefits.

This paper describes currently available heat pump water heating equipment and offers guidelines for successful applications in commercial facilities. The results of field test programs involving more than 100 units in Alabama, Georgia, Mississippi, Tennessee, South Carolina, and other areas are incorporated. Initial conclusions are drawn from a reliability database, and interviews with utility applications specialists and manufacturers are discussed. Design tools are reviewed, including a new comprehensive computer simulation model. Emphasis is placed on identifying sound candidates for installations and on application and design considerations. A brief survey is provided of environmental implications of heat pump water heaters and new developments in heat pump water heater equipment.

INTRODUCTION

Heat pump water heaters (HPWHs) offer an extremely efficient means of heating water for commercial facilities. Typical air-source heat pump water heaters are four to five times more efficient than gas water heaters and about three times more efficient than conventional electric units. In addition, the heat pump water heater's cooling effect can usually be applied to a useful purpose, further increasing the value of the system. Operating in this dual role, a heat pump water heater uses simple refrigeration technology to simultaneously accomplish two useful thermal functions.

HPWHs have been used effectively throughout the United States in a variety of climates and facilities. There are numerous examples of successful heat pump water heater installations in laundries, restaurants, hospitals, nursing homes, hotels, apartment buildings, health clubs, and other commercial facilities. Because HPWHs heat water by extracting heat from their surroundings, they function more efficiently in hot, humid environments.

At typical energy costs, HPWHs provide hot water less expensively than gas. In addition, HPWHs offer tangible benefits other than energy and cost savings. Frequently, overheated spaces and water heating loads are closely associated. HPWHs can address common customer problems of overheating, poor comfort conditions, and inadequate ventilation. The HPWH's readily perceived cooling benefit is an advantage over conventional water heating alternatives. The value of improved comfort conditions in employee productivity and customer satisfaction can exceed the simple energy cost savings. Water heating with HPWHs leads to the release of less CO_2 to the environment than electric resistance and combustion water heating technologies.

Interest in HPWHs is growing. Recent releases of a HPWH applications handbook, technical literature, and analysis tools simplify evaluation of alternatives and system design.

TECHNOLOGY BACKGROUND

A heat pump water heater (HPWH) uses simple refrigeration technology to accomplish an ingenious high-efficiency thermal function. Electric energy is used to draw heat from the surroundings and produce hot water. In the case of a typical air-source HPWH, heat is removed from the air, producing a cooling effect useful for space cooling and dehumidification. At the same time, the heat removed from the air and most of the electric energy are used to heat water. Two useful energy flows or beneficial effects result from one energy input.

The basic operation of a heat pump water heater can be readily understood by examining it as a black box, without regard to its inner workings. Using this simplified approach, Figure 1 illustrates the three energy flows involved with a typical heat pump water heater. Two of the energy flows are directed into the heat pump: the HPWH consumes electric energy and it removes heat from the surrounding air, producing a cooling effect. The third energy flow is the useful heating effect produced by the HPWH.

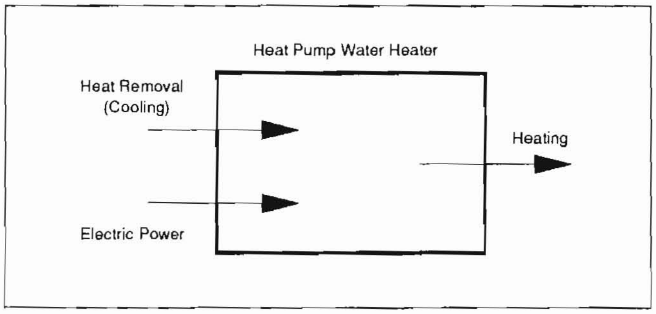

Figure 1. HPWH Energy Flow

The electric energy input results in two useful outputs: heating and cooling. The heating output is applied to a water heating load. Commercial HPWHs deliver their cooling effect directly to the interior of a building or to a mechanical system that routes it to the building interior for spot cooling.

Under typical conditions, an air-source HPWH operates with a coefficient of performance (COP) of approximately 3.0, delivering about 10,000 Btuh of water heating for every kilowatt of electric power it uses. Typically, the maximum output temperature is limited to about 140° F. The HPWH also provides a cooling effect of about 6,700 Btuh per kilowatt. Like a conventional air conditioner, about 75% of the cooling output is sensible cooling and 25% is latent cooling or dehumidification at 75° F dry-bulb temperature and 50% relative humidity.

Although heat pump water heaters are available in a wide range of configurations, capacities, and operating modes, air-to-water HPWHs are the most common in commercial applications. These HPWHs are the focus of this paper. Air-to-water HPWHs are available in water heating capacities from 8 to 480 kBtuh.

Heat pump water heaters are seldom designed to meet the entire water heating load and must rely on a conventional source of heat to supplement their output. The interface between a HPWH and a conventional supplemental water heater takes one of two forms: stand-alone or preheat. Stand-alone systems, shown in Figure 2, include all the HPWH components and supplemental electric water heater in a single package that completely replaces the conventional water heater. These systems are simple and require no additional floor place, making them attractive for fast food restaurants and other facilities where floor space is at a premium.

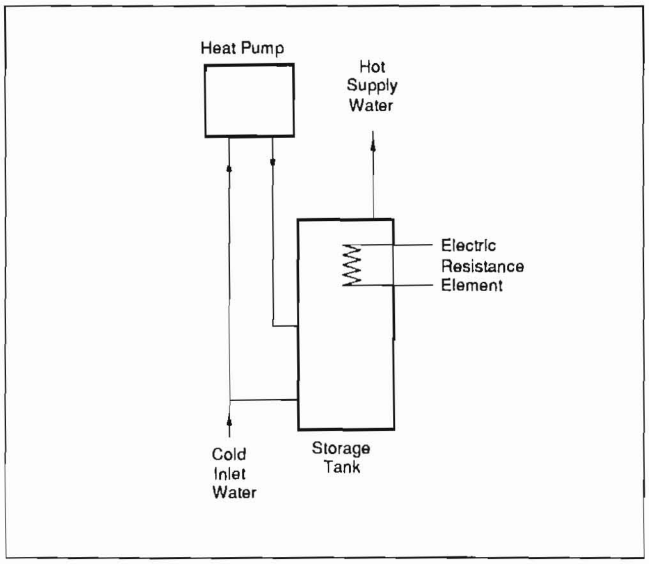

Figure 2. Stand-Alone HPWH System

Preheat systems, illustrated in Figure 3, have a separate hot water storage tank and work in series with a conventional supplemental water heater. The heat pump delivers heat to the storage tank, which preheats cold cold inlet water before it enters the conventional water heater. Preheat systems have a larger storage volume and are more common when higher heating capacity is required. Preheat systems can be used with both electric and gas supplemental water heaters.

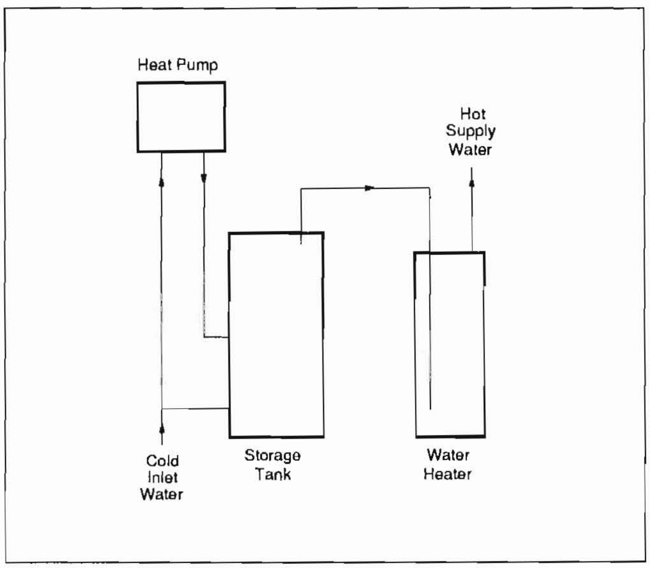

Figure 3. Preheat HPWH Systems

HPWH operation is usually controlled by a simple thermostat that senses water temperature in the storage tank. The HPWH operates in response to the water heating load only. In instances where the HPWH might overcool the space, a space thermostat is added in series with the tank thermostat. This control scheme allows the HPWH to operate only when there is a water heating load and a simultaneous need for cooling. If the space is also served by a conventional air conditioner, a single multi-stage thermostat controls the HPWH and the air conditioner. The HPWH is operated as the first-stage cooling device.

Most HPWHs operate in the combined water heating and cooling mode. This mode of operation is the most efficient because two useful energy outputs are produced for a single energy input. When cooling output must be available on demand, regardless of water heating load, a HPWH capable of operating in the cooling-only mode can be installed. In cooling-only mode, these units reject heat to an auxiliary condenser instead of a water heating load. They are typically less efficient than conventional air conditioners, although recent equipment developments promise improved performance. Installation of a high-efficiency air conditioner and standard, combined-mode HPWH may be more attractive.

HPWH PERFORMANCE

Operating Conditions

Typical air-to-water heat pump water heaters with indoor evaporators are designed to function at an air temperature of about 45° F to 120° F. Performance declines at the extremes of the range. Outside this range, high and low pressure switches stop operation. Incoming water temperature of 40° F to 135° F is tolerated by most units.

Influences on Performance

The performance of an air-to-water heat pump water heater is strongly affected by the wet-bulb temperature of the air flowing over the evaporator. Higher wet-bulb temperature results in greater heat transfer through the evaporator, which yields greater cooling and water heating output and better efficiency. The warm, humid environment found in kitchens and laundries is particularly well-suited for efficient heat pump water heater operation.

Figure 4 illustrates the variation in water heating output with evaporator wet-bulb temperature for a typical air-to-water HPWH. At normal conditions, each one-degree increase in wet-bulb temperature results in a one to one and one-half percent increase in water heating output and COP. Cooling output increases from one and one-half to two and one-half percent per degree of wet-bulb temperature increase.

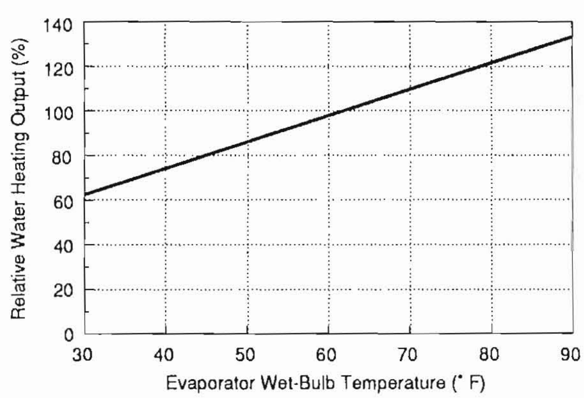

Figure 4. Effect of Evaporator Wet-Bulb Temperature on HPWH Output

Performance is also affected by the water temperature at the HPWH condenser. HPWHs operate more efficiently at lower condenser temperature and lower temperature lift. (Temperature lift is the difference between the temperature of the heat source and the heat pump hot water output temperature.) The smaller the temperature lift, the higher the efficiency and the greater the thermal output. Figure 5 illustrates the effect of entering condenser water temperature on water heating output at a fixed hot water output temperature for a typical air-to-water heat pump.

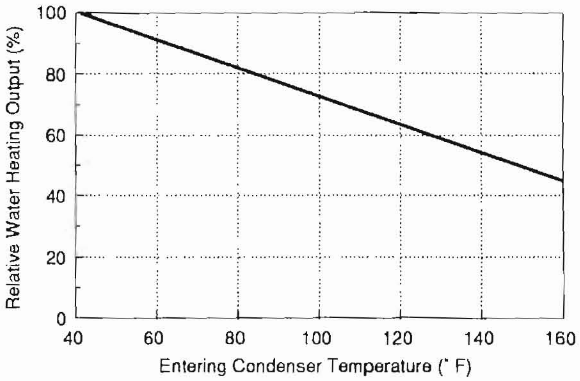

Figure 5. Effect of Entering Condenser Water Temperature on HPWH Performance

The best HPWH applications are those that allow the heat pump to operate with low temperature water and a small water temperature increase.

Enhancing Performance

HPWHs function best where the inlet water temperature is low and where the air in the space to be cooled is warm and humid (Table 1). There can be a difference in output and efficiency of 40% or more for reasonable variations in operating conditions.

Case 1		Case 2
55	Inlet water temperature (°F)	55
135	Tank temperature (°F)	135
95	Air temperature (°F)	75
70	Relative humidity (%)	50
3.6	Water heating COP	2.9
65,400	Water heating output (Btuh)	50,000
47,100	Cooling output (Btuh)	31,500

Table 1. Effect of Operating Conditions on HPWH Performance

HPWH Ratings

The U.S. Department of Energy (DOE) defines test procedures for residential HPWHs with a maximum current rating of 24 amperes at a voltage no greater than 250 volts. Test results are published semi-annually by the Gas Appliance Manufacturers Association (GAMA) in a publication entitled *Consumers' Directory of Certified Efficiency Ratings for Residential Heating and Water Heating Equipment*.

This DOE test procedure became effective on October 15, 1991, replacing a procedure developed by GAMA in the early 1980s. Changes in the test procedure had a significant impact on the published performance figures for HPWHs. For one typical HPWH model, the first-hour rating dropped by 2% and the energy factor decreased by 46% under the new test procedure. The primary cause is a reduction in the ambient temperature from 75° F to 67.5° F.

It is important to note that the DOE test procedure bears little resemblance to water heating loads and conditions that a commercial HPWH normally encounters. However, until a commercial test is available, this procedure is the default standards for rating HPWHs. HPWH manufacturers publish performance data for their commercial units based on the DOE test.

APPLICATIONS CONSIDERATIONS

Efficiency

At typical operating conditions, a HPWH delivers 2.5 to 3.0 units of heat for each unit of energy purchased. Compared to electric resistance water heaters which are 90% to almost 100% efficient, the HPWH delivers the same heat for about one-third the energy input. HPWHs are four to five times more efficient than gas-fired water heaters.

Operating Energy Cost Comparison

To provide one million Btu of water heating energy, a typical HPWH consumes 99 kWh of electricity. Using national average commercial energy costs for 1991 of \$0.075/kWh and \$0.476/therm, water heating by the HPWH would cost \$7.45. A typical electric resistance water heater consumes 318 kWh at a cost of \$23.89. A gas water heater consumes 16.7 therms of natural gas at a cost of \$7.93. The HPWH produces hot water at 31% of the electric resistance water heater energy cost and 94% of the gas water heater energy cost.

The following annual efficiency ratings or energy factors are used here.

HPWH	2.95
Electric resistance storage water heater	0.92
Gas storage water heater	0.60

These figures were selected from the April 1991 GAMA directory and represent median efficiencies of the models listed. These figures were used instead of revised test results because they are more representative of typical commercial operating conditions.

Value of Cooling

HPWHs also provide useful cooling while operating to heat water. In the example above, the HPWH provided 660 kBtu or 55 ton-hours of cooling while producing one million Btu of hot water. The cooling output carries benefits. It can improve occupant comfort through spot cooling, making workers more productive and decreasing employee turnover. It can also solve equipment overheating problems, improving ice maker output or cooling electrical switchgear. It can reduce the initial cost of additional conventional air-conditioning equipment or the cost of maintaining old equipment.

One way to establish an economic value of HPWH cooling output is to calculate the cost of providing the cooling with a conventional air conditioner. The cooling value depends on the efficiency of that air conditioner – the lower the efficiency, the greater the HPWH cooling value. Assuming a seasonal energy efficiency ratio (SEER) of 10.0, an air conditioner would consume 66 kWh to produce the same 660 kBtu of cooling delivered by the HPWH in the example as a byproduct of water heating. Using \$0.075/kWh, the value of the HPWH's cooling is \$4.96. The net cost of operating the HPWH is \$2.49 (\$7.45 water heating cost – \$4.96 cooling value).

The cost of one million Btu of cooling effect can be estimated by the following equation:

$$\text{Cost (\$/mBtu)} = \frac{\text{Energy Cost (\$/kWh)} \times 1000}{\text{EER (Btuh/Watt)}}$$

If HPWH cooling output actually displaces the operation of an air conditioner, total cooling costs will decline. However, because HPWHs are typically installed in areas with inadequate cooling capacity, owners do not realize direct cost savings in most applications. The HPWH improves comfort or solves other overheating problems and supplements air conditioner operation rather than displaces it.

Relative Energy Costs: Electricity vs. Gas

Figure 6 provides a comparison of the relative costs of water heating energy from HPWHs and gas water heaters. The solid line describes pairs of gas and electric energy costs where a HPWH operating at a COP of 3.0 produces hot water at the same cost as a gas water heater operating at an instantaneous efficiency of 70%.

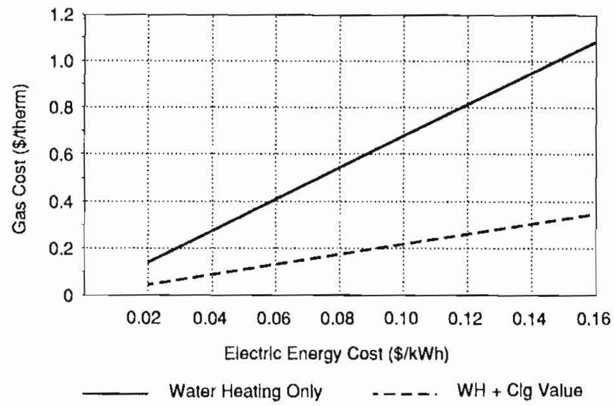

Figure 6. Comparison of Relative Costs of Water Heating Energy From HPWHs and Gas Water Heaters

The broken line includes the value of cooling produced by the HPWH. The energy cost of operating a conventional air conditioner with an EER of 10.0 is subtracted from the energy cost of operating the HPWH.

For typical gas and electric rates, considering water heating only, a HPWH provides hot water at or below the cost of water heated by gas. When the value of cooling is considered, the net cost of water heating is lower for a HPWH.

Environmental Impact

The generation and release of CO_2 is considered to be a major contributor to global warming. Considering all effects, including source energy at the power plant and distribution loss, HPWHs cause the release of less CO_2 than any other conventional water heating technology. To provide one million Btu of heat to a water heating load, the electricity consumed by the HPWH will cause the release of 147 pounds of CO_2 into the environment. To accomplish the same task, an electric resistance water heater will result in the release of 471 pounds and a gas-fired water heater 192 pounds. With credit for its cooling output (compared to conventional air conditionig with EER = 10.0), the net release of CO_2 for water heating is only 49 pounds. High-efficiency HPWHs with improved air-conditioning performance are kinder and gentler to the environment. A HPWH with a water heating COP of 4.0 will cause the release of 108 pounds of CO_2 while producing one million Btu of hot water. The 750 kBtu of cooling effect produced by the HPWH would result in the release of 111 pounds of CO_2 if produced by an air conditioner with an EER of 10.0. By taking the place of the air conditioner, the HPWH causes a net reduction in the release of CO_2 while providing hot water and cooling.

SUMMARY OF HPWH MARKET

Manufacturers, Costs, Types

Nine manufacturers currently sell air-source HPWHs with water heating capacities from 8 to 480 kBtuh. Three of these manufacturers build only units with water heating requirements of 24 kBtuh capacity or less. Installed costs for commercial HPWHs range from $120 to $170 per kBtuh of water heating capacity.

Several manufacturers offer custom-built units with higher heating capacity, additional features, and control options. These units are more expensive.

HPWHs are 5 to 10 times more expensive to purchase and install than conventional storage-type gas and electric water heaters. If low installed cost is the principal concern, HPWHs are not the answer. Where investment capital is available, the added initial cost may be recovered by ongoing energy savings. Simple payback periods of less than three years are found in good applications.

Utility Activity

Since several utilities began limited testing and monitoring of commercial HPWHs in the mid-1980s, utility interest, involvement, and support of HPWH commercialization have grown. Georgia Power Company has installed 55 units in a large-scale testing program. Wisconsin Electric, through a rebate program which began in 1987, is responsible for more than 200 commercial installations. Low interest loans and design support provided by Mississippi Power Company resulted in 60 installations during 1990.

Electric utilities view HPWHs as an attractive option. Their high efficiency and high load factor are useful for load management. HPWHs solve customer problems, and they offer hot water at a cost roughly equivalent to that of gas water heating.

Chains

Several large retail and service chains have adopted HPWHs. BI-LO, Inc. has installed 30 HPWHs in its supermarkets in Georgia and South Carolina. Kwik Wash Corporation, operator of a 200-store coin-op laundry chain, has installed more than 60 units in its stores. Based on favorable experience with Wisconsin Electric's program, several fast-food chains have used HPWHs in new Wisconsin stores.

GENERAL APPLICATIONS GUIDELINES

Heat pumps are not a universal solution to water heating and space cooling energy cost reduction. Potential applications should be evaluated to select sites that offer the best performance and return on investment. Prime applications for HPWHs have simultaneous water heating and cooling loads. Several factors contribute to the success of an application.

HPWH Run Time

Run time is the most important application consideration. HPWHs produce savings only when operating. The more they operate, the greater the savings and the faster the payback on added installation cost. For the best economic return, it is better to undersize a HPWH system than to oversize it. Both water heating load and cooling load must be considered in evaluating potential run time.

Value of Cooling Output

HPWHs are most valuable where additional cooling capacity is required and where the value of cooling is recognized. Under some circumstances, the HPWH's cooling output can allow reduction of the conventional air-conditioning system capacity.

Validity of Loads and Loads Data

Load information used for design and analysis should be treated skeptically unless it is the result of direct measurements. If estimates are used, the effect of overstating and understating the loads by 50% to 100% or more should be investigated. Owner estimates of hot water usage are often unrealistic.

Storage Capacity

One rule of thumb for tank sizing used successfully in Hawaii calls for a HPWH storage tank capacity equal to the heat output of the heat pump operating for 1.5 to 2.5 hours. A 60° F temperature increase in the tank is assumed.

Increased storage capacity increases the ability of a water heating system to meet peak loads. The HPWH operates during the periods of low hot water demand and stores heat in the tank. When a large hot water load occurs, it can be met by both the heat output of the HPWH and the heat stored in the tank. The maximum total hot water delivery capacity during a one-hour period is approximately equal to the HPWH capacity plus 85% of the stored energy. For example, a 50-kBtuh HPWH can produce approximately 75 gallons per hour of hot water at an 80° F rise. With a fully charged 100-gallon storage tank, a peak one-hour load of 160 gallons (75 + 100 x 85%) can be met.

Hot Water Temperature

Most HPWHs can produce hot water with a maximum temperature of approximately 140° F. Where the required hot water temperature is greater than the maximum HPWH output temperature, supplemental heating is required. Usually, a HPWH should function as a preheater for warming cold water, while a supplemental water heater provides the final temperature boost.

Heat Pump Water Heaters for Cooling

A HPWH is seldom a substitute for an air conditioner and should not be expected to operate like an air conditioner. Typical HPWHs cannot operate for cooling on demand, but only when water heating is required. Where cooling is required on demand, regardless of the water heater load, a HPWH capable of operating in the space-cooling-only mode must be used. The efficiency of a HPWH in the cooling-only mode is probably lower than that of a comparable high-efficiency conventional air conditioner. Consequently, where significant cooling-only operation will be necessary, the best design may be a smaller HPWH coupled with a high-efficiency conventional air conditioner.

Application Checklist

The following checklist provides a summary of key HPWH application considerations.

Heat Pump Water Heater Application Checklist

- ☐ Are basic utility rates favorable for HPWH?
- ☐ Is the water heating load a valid load?
- ☐ Have water temperature limits been recognized?
- ☐ Is there a source of waste heat or air-conditioning load?
- ☐ Is the heat source or air-conditioning load available throughout the entire year?
- ☐ If the facility is currently air conditioned, is the existing cooling equipment too small to meet the load?
- ☐ Is the installation of additional air-conditioning capacity planned?
- ☐ Is the existing air-conditioning equipment to be replaced?
- ☐ Will the cooling load be valued? If not, can the HPWH compete with the conventional system on water heating savings only?
- ☐ If HPWH cooling output is needed continuously, is the water heating load adequately large, or can a remote condenser be installed?
- ☐ Is electric service available at the required voltage and ampacity?
- ☐ Is there adequate space to install the HPWH and any required additional storage tanks?
- ☐ Are ambient conditions suitable for HPWH operation?
- ☐ Is capital available to finance the installation?
- ☐ Are low-cost loans, grants, tax benefits, or utility incentive programs available?

DESIGN AND ANALYSIS RESOURCES

HOTCALC 1.0

The Electric Power Research Institute's HOTCALC software models five commercial water heating technologies: heat pump water heaters, electric storage water heaters, gas storage water heaters, refrigeration heat reclaim, and waste heat recovery. HOTCALC quickly assesses the performance of various alternative system designs.

Detailed input and dynamic modeling of system performance using fractional hour time steps yield flexibility and accuracy. A user-friendly interface with default input data, context sensitive help, and both summary and detailed results make HOTCALC easy to use.

COMTECH 3.0

EPRI's *COMTECH 3.0* software is used to model commercial building designs and evaluate the effects of alternative space heating, cooling, water heating, and cogeneration options on energy use and operating cost. COMTECH uses either its own simplified water heating analysis model or a data file created by HOTCALC to examine water heating loads in the context of the entire facility's load. Alternative rate schedules can also be evaluated.

Simple Run Time Calculations

Simple screening calculations for HPWH savings and run time can be made using nomographs (Figure 7) contained in EPRI's *Commercial Heat Pump Water Heater Applications Handbook*, EPRI CU-6666.

Figure 7 uses the daily water heating energy requirement to estimate HPWH run time and air-conditioning value. When selecting an energy requirement figure, be sure to consider the fraction of the load to be provided by the heat pump.

Enter along the left side in section A with the net daily water heating energy requirement. Move right to the approximate *water heating* capacity of the HPWH, in kBtuh. Daily HPWH run time is then read from the horizontal scale at the upper edge of section A.

Daily air-conditioning energy value can also be estimated. Move right from the intersection of the daily energy requirement line and the water heating capacity line to the line representing the approximate EER of the conventional air-conditioning system. Then move up to the scale at the edge of section B to read daily electric energy value. The figure obtained is the electric energy consumption by conventional air conditioners to provide the same cooling output.

Example: For a 400 kBtuh/day water heating load, what would be the approximate daily run time for a 30 kBtuh HPWH? What air-conditioning energy value would be produced? The conventional air conditioner is an old system with an EER of approximately six.

Enter the nomograph at the left edge with a water heating energy requirement of 400 kBtu/day and move right to the 30 kBtuh water heating capacity line. From the intersection, move upward. Run time is read from the top of the nomograph as approximately 13 hours per day.

Air-conditioning value is found in section B of Figure 7. Move right from the intersection of the water heating energy requirement and water heating capacity lines to the line for an EER of six. Then move upward to the edge of section B to read 45 kWh of daily value in conventional air-conditioning system operating energy.

These nomographs assume good load coincidence and should be considered upper limits of the actual performance to be expected.

Reports

Commercial Heat Pump Water Heater Applications Handbook, EPRI CU-6666, Electric Power Research Institute, 1990

Handbook of High-Efficiency Electric Equipment and Cogeneration System Options for Commercial Buildings, CU-6661, Electric Power Research Institute, 1989

Heat Recovery Heat Pumps in Commercial Buildings, EPRI EM-5464, Electric Power Research Institute, 1987

User's Guide for COMTECH 3.0: *A Screening Tool for Commercial Building Technologies*, Electric Power Research Institute, 1992

Brochures

Heat Pump Water Heaters, an Efficient Alternative for Commercial Use, EPRI EU-2020, Electric Power Research Institute, 1990

Copies are available from:

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CONCLUSIONS

- HPWHs are a high-efficiency electric technology. HPWHs have demonstrated that they can meet published performance figures, operating reliably and efficiently. Typical HPWHs operate with an annual water heating COP of 2.5 to 3.0 and produce about 0.67 Btu of cooling per Btu of water heated.
- HPWHs heat water at a cost roughly equal to that of gas water heaters. Using average commercial energy costs for 1991 of $0.075/kWh and $0.476/therm, a HPWH operating with an energy factor of 2.95 produces hot water for $2.45/mBtu, compared to $7.93/mBtu for a gas water heater with an energy factor of 0.60.
- HPWHs solve cooling problems; the cooling output is frequently more important to the building owner than energy savings. HPWHs provide spot cooling to alleviate discomfort at work stations or to condition areas not readily served by conventional air-conditioning systems. HPWH cooling output can reduce overheating to improve equipment performance, provide redundant capacity, and avoid central plant expansion.
- Run time is the key to successful applications. HPWHs generate savings only when they are operating. HPWHs should never be oversized.
- Basic design and installation must be done correctly. HPWHs are simple devices and almost all problems observed have been due to simple mistakes. Poor basic plumbing installation is the largest cause of operational problems. Diligence, following the manufacturer's instructions, and the use of a simple checklist during start-up can prevent these difficulties.
- HPWHs are nearly maintenance free, but filter cleaning or replacement is essential. HPWH users should be briefed on the simple maintenance requirements and how to recognize equipment faults. A routine of scheduled maintenance should be followed.

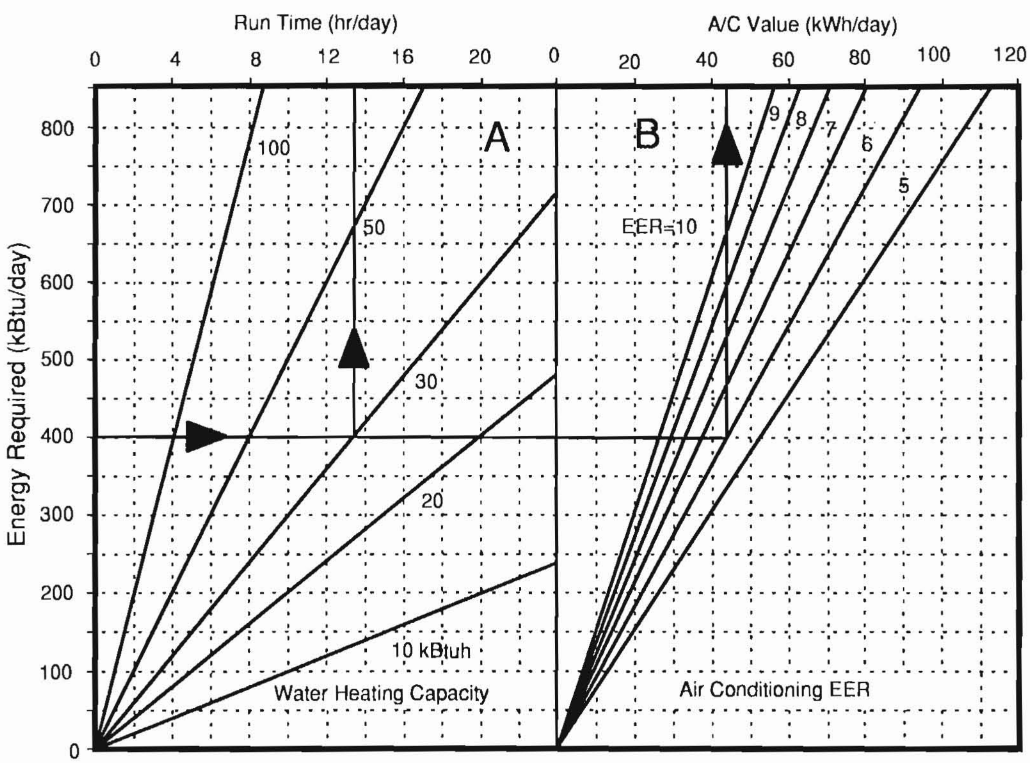

Figure 7. Example – HPWH Run Time and Air Conditioning Savings