A Comparative Study of High-Efficiency Residential Natural Gas Water Heating

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ABSTRACT

Residential water heating accounts for 1.15 quadrillion Btu of natural gas use each year, nearly a quarter of all natural gas used in U.S. households. More than 50 percent of U.S. households rely on natural gas for water heating. To address this large end-use, gas efficiency programs around the country promote higher-efficiency, natural gas storage-type water heating technologies. As storage-type water heaters approach their technical limits of efficiency, program administrators are starting to look for alternative technologies capable of higher efficiencies. This paper provides a summary comparison of various high-efficiency gas water heating technologies currently available.

The authors examine the following for several gas water heating technologies: appropriate applications; range of efficiencies; market barriers; and other characteristics crucial in considering promotion within an efficiency program. Three major technologies are considered: standard and condensing storage water heaters; instantaneous heaters, also known as "tankless" or "on-demand" units; and combination systems, where a single piece of equipment is used for both space-heating and domestic hot water. The authors outline the differences in technology that yield varying efficiencies and then summarize the technical, safety, and application limitations of each that could affect its promotion in efficiency programs.

Introduction

As of 1997, water heating accounted for 19 percent of the total site energy[1] used in the average United States household (EIA 1997). More than 50 percent of U.S. households rely on natural gas for water heating. Residential water heating accounts for 1.15 quadrillion Btu of natural gas use each year, nearly a quarter of all natural gas used in U.S. households (EIA 2003). Water heating is the second largest energy end-use in households – space conditioning being the largest – and as such is a natural area of focus for programs promoting efficiency.

A recent survey of gas efficiency programs around the country found that 22 states had utility-funded programs (Kushler et al. 2003). More than half of these states have utility-sponsored programs promoting high-efficiency gas water heating. These programs collectively promote as efficient all three types of water heaters described in this paper including instantaneous and combination systems. However, most programs limit their incentives to storage type heaters with efficiencies ranging from 10-15 percent above the federal minimum.

The federal minimum standard for gas water heaters (as well as other fuel types) increased in January 2004. This new standard is close to the levels of efficiency being promoted through utility and other efficiency programs. While this standard effectively raises the "floor" of

[1] "Site Energy" and other terms used throughout the paper are defined in a Glossary located after the Conclusions.

efficiency, utilities and others administering gas efficiency programs may still be looking for opportunities to promote even higher levels of efficiency.

Increasing the efficiency of installed products is the ultimate goal of energy efficiency programs, but this cannot be achieved at the expense of reliability, safety, reasonable cost, or customer satisfaction. Incentives for certain levels of efficiency or kinds of technology are often perceived as endorsements of products with higher quality and other benefits besides efficiency. While perhaps not technically liable for any product defects, most utilities zealously avoid association with products that might negatively affect their customers' satisfaction. Potential risks include exaggerated efficiency claims, safety concerns, reliability, poor water quality, and insufficient flow. To design successful efficiency programs, administrators must understand the potential benefits and limitations of each efficient gas water heating technology.

Technology Overview

There are three major types of natural gas water heating systems used for residential applications. The most common by far is an insulated storage tank with a burner underneath. Less common in the United States, though almost standard in Europe and Japan, are tankless or on-demand water heaters. The third type of heater is a combination system that provides both space heating and potable hot water heating. Here, each type of heater is described along with any limitations on application or operation.

Storage Tank

The vast majority of installed gas water heaters are the storage-type. They consist of an insulated, glass-lined, steel storage tank, and an inexpensive gas burner underneath. The burner vents through a baffled, central flue that runs up through the middle of the tank and serves as a second heat transfer surface. The typical gas input for storage tanks is 40,000 Btu/h (42 MJ/h) for a 40 gallon (151 liter) unit (DOE 2000), though input ranges from 38,000 Btu/h (40 MJ/h) for 30 gallons (114 liters) up to 75,000 Btu/h (79 MJ/h) for a 100 gallon (378 liter) unit (GAMA 2004a).

The burner of storage water heaters turns on periodically throughout the day and night to maintain the temperature of the water in the tank at a preset temperature, typically 120 - 140° F (49 - 60° C). Most storage water heaters have a continuously burning, or standing, pilot light, the heat from which helps to maintain the tank temperature.

Condensing storage water heaters transfer more heat from the burning fuel to the water, resulting in combustion products that are cool enough to cause the water vapor to condense. High efficiency gas furnaces operate in a similar manner. Condensing water heaters have efficiencies approaching 90 percent. While common in the commercial market, few if any residential sized units are available today. A few models designed for commercial applications are sometimes used for combined space and water heating in residential applications (DOE 2000).

The current federal standard metric for water heater efficiency is Energy Factor (EF), a measure that accounts for both recovery efficiency (the ratio of energy delivered to the water to energy consumed) and standby losses. The federal minimum standard was most recently raised for residential gas water heaters on January 20th, 2004. It increased by approximately 10 percent over the previous minimum. Of the 30-100 gallon (114-379 liter) models now available, and qualifying for the new standard, EFs range from 0.48 to 0.65 (GAMA 2004a).

Heat is lost through the flue and through the tank's sides and fittings. Most of the improvements to efficiency for storage type water heaters have come from reducing standby, conductive losses through better and more insulation. There are, however, limits to how much insulation can be used because replacement units must often fit into a space sized for an older, less insulated unit. There are also diminishing returns to added insulation, with fewer savings available for each added inch of insulation.

Limitations. Storage-type water heaters are the norm across the country with over 5 million shipped in 2003 (GAMA 2004b). Their biggest drawback is their efficiency relative to alternative gas technologies. These units are typically vented through a chimney or straight up through the roof but can also be power vented through an exterior wall. Condensing-type heaters require specialized installations to accommodate the corrosive condensate caused by the low temperature flue gases.

Tankless

Tankless water heaters, also known as on-demand or instantaneous, represent less than 1 percent of the installed base in the US (DOE 2003a). They are, however, quite common in both Europe and Asia, where their compact size and low standby losses contribute to their popularity. On-demand water heaters heat the water only as it is needed, as opposed to drawing if from a storage tank, so there are no appreciable standby losses. Additional efficiencies come from eliminating the standing pilot light. While some tankless units have a standing pilot light while others use an electronic or intermittent ignition device (IID). This device is either powered by batteries or connected to a permanent power source. While these electronic devices or other controls can have some standby draw, the energy used is still less than for a standing pilot light. Energy Factors for tankless units range from approximately 0.64 (for a small unit with a maximum input of 40,000 Btu/h, 42 MJ/h) to 0.85 (for a unit with a maximum input of 175,000 Btu/h, 185 MJ/h).

Older units raised the temperature of the water a set amount while new models are thermostatically controlled so that they produce water at a fixed output temperature, modulating the burner in response to changes in inlet water temperature. The current design is much safer, using thermostat controls to eliminate the possibility of scalding from low flow demand or high input water temperature. A homeowner might try to set the thermostat higher than is safe to improve flow, but this problem exists with storage water heaters as well, where the thermostat can be set above a safe range.

The capacity of tankless units is measured in flow (in gallons or liters) per minute rather than in flow per hour, or "first hour rating", used for storage tanks. Flow rates vary based on the required temperature change between the incoming and outgoing water. Capacities for units on the market vary from 1 to 6 gallons per minute (4–23 liters/min), though there are larger units (up to 8 gal/min or 30 l/min) available overseas. A minimum of 3 gallons per minute with a 77° F temperature rise (11 l/min, 43° C) is required by the typical household, so units at the high end of this scale are likely adequate to meet the flow requirements of a reasonably water-efficient household (DOE 2003a).

Modulating units deliver water at a constant temperature regardless of flow rate, varying the firing rate of the burner to meet larger flow needs. This is preferable to a unit that simply restricts the input flow to maintain the same output temperature when it can't meet the full flow demand at the required temperature. Condensing technology can be used for tankless water heaters but such units are not yet available in the United States and are still uncommon in markets where tankless heaters are more established.

Limitations. Relative to tank-type heaters, on-demand units offer diminished flow rates and are therefore most appropriate where flow requirements are smaller. Small homes with efficient water using appliances and outlets are more likely to be adequately supplied from a tankless unit. When choosing a heater, a consumer must calculate his or her flow requirements based on the needed temperature rise, size and number of fixtures, and use schedule.

In some situations, replacing conventional water heaters with instantaneous water heaters may result in inadequate gas pressures unless the old gas piping is replaced with larger diameter pipe. Tankless units average 150,000 Btu/h (158 MJ/h) draw (often modulating between 15,000 and 190,000 Btu/h, 15.8–90 MJ/h) as compared to a storage type with a typical draw of 40,000 Btu/h (42 MJ/h). This problem is more common in older homes. The supply line can usually be replaced with a larger one, though this would add to installation costs.

Mineral build-up or scaling can also be a problem with instantaneous water heaters, more so than for storage units, because the channels within the heat exchanger are smaller and internal temperatures typically hotter. In areas with hard (high mineral content) water, proper installation requires a pre-filter to treat the water before it runs through the heating unit. Another way to reduce scaling is to blow hot air over the heat exchanger rather than using the flame directly on the exchanger itself. Where excess silt in the water is the actual problem, a plumber can easily prevent clogging by placing a tank (not a heating unit) before the water heater to give the sediment a place to settle out.

Combination Systems

There are two basic kinds of combination space and water heating systems discussed here. One uses a water heater to provide domestic, potable hot water and to feed a radiant, baseboard, or warm-air heating system. The other uses a boiler to feed hydronic or radiant heating and to heat potable water. While some combination systems can lower initial capital costs because only one piece of equipment is needed, not all systems offer greater efficiency than separate water and space heating equipment. This section focuses primarily on the system designs that provide greater efficiency than stand-alone, separate heating systems.

Where a water heater is used for space heating, the more common system uses a high-input storage tank heater that also feeds radiant pipes or an air handler. Tankless water heaters can be used to feed radiant piping, though the overall heating load (space and water) will need to be relatively small to be met by the lower capacity tankless unit. Such a combination system might only be appropriate for a small, well-insulated home or a remote wing of a home.

There are several ways that a boiler can be used for both space and water heating. One inefficient and somewhat antiquated method is to fit a standard boiler with a sidearm or tankless coil to heat potable water. A separate loop carrying potable water is pumped though the boiler vessel. Since this system doesn’t have a storage tank, the flow rate is limited and consumers have complained of running out of hot water. Additionally, since the boiler must operate year-round and fire whenever hot water is drawn, system efficiency in the summer can be quite low. Efficiency program administrators do not recommend this type of system for efficiency purposes.

The most efficient boiler-based combination system uses an indirect-fired water heater. Here, a boiler feeds a heat exchanger inside a storage tank (typically 50-100 gallons, 189-378 liters), transferring heat to the potable hot water. This system takes advantage of the already-hot boiler during the heating season. The storage capacity and insulation on the tank allow the boiler to fire less frequently when there is no space heating load (DOE 2003b). Condensing boilers with heat purging controls yield even greater efficiency since they circulate residual heat from the heat exchanger into the water storage tank. One other advantage of using a boiler for water heating is the typically long life of boilers, 30 or 40 years compared to 10 to 15 years for a standard water heater. This long lifetime contributes to the relative cost-effectiveness of a combination system.

Energy Factor is not the only metric used for rating the efficiency of combined systems. In 1991, the American Society of Heating, Refrigeration, and Air-Conditioning Engineers approved a standard testing and rating method for combination equipment (ASHRAE 1991). The overall system efficiency is reported as the Combined Annual Efficiency (CAE), which allows comparison between different combination systems.

In addition, each unit also has a rating that can be used to compare it to a stand-alone boiler or water heater. These are CA_{AFUE} and CA_{EF}, analogous to Annual Fuel Utilization Efficiency and Energy Factor, respectively. For example, CA_{EF} can be compared to the EF of a stand alone water heater to determine which is more efficient at water heating (Thorne 1998).

Combination systems are subject to the federal minimum efficiency levels prescribed for stand-alone space or water heating systems but in a different way. The primary heating equipment is subject to the same standards for stand-alone equipment of the same type, i.e., where a boiler heats potable water, the system must meet the minimum for boilers (currently 80% AFUE) and where a water heater is used for space heating, it is the water heater minimum EF that applies.

Limitations. Certain combination systems can be appropriate for most residential applications. However, they are easiest and most economical to install in new construction or situations where both a boiler and heater need to be replaced. As stated earlier, some combination systems have low recovery rates and are not particularly efficient. Since there are combination systems available that are much less efficient than stand alone space or water heating equipment, it is critical that consumers consider the relative efficiency ratings in comparing systems.

A major barrier to combination products becoming more popular in the market is their high first cost, particularly when compared to stand-alone, storage-type water heaters. Boilers are expensive, but they can last a long time. Since many consumers still make purchase decisions based on the first cost without considering operating costs, combination systems with boilers are disadvantaged. Prices are also kept high by limited competition and contractors' unfamiliarity with the products (Thorne 1998).

If water in the hydronic system mixes with the potable water, there is the potential for stagnate water to cool to tepid temperatures, allowing the growth of certain bacteria, including *legionnella*. This can be overcome by either making sure the potable water is separate from the hydronic system or by installing a pump timer to automatically flush water through the system.

Program Considerations

When developing programs, administrators must consider more than simply the energy savings of a particular product type. The following summarizes the most crucial factors used in comparing products and deciding whether to promote them to customers.

Efficiency and Savings

One of the difficulties for efficiency program administrators trying to promote better water heating is the problem of comparing the efficiencies of different systems. As described above, both storage-type and tankless water heaters must use EF to describe efficiency. With combination systems, there is both the combined annual efficiency (CAE) as well as CA_{EF} or CA_{AFUE}. Though a fair amount of product-specific information is available on the web, explanations of these different ratings are difficult to find. Furthermore, since the federal minimum standard only applies to the primary heating equipment, it can be confusing to see a very low EF on a boiler combination system. On top of this, even though EF is the federally regulated efficiency metric, it is not always prominently displayed on water heaters in retail stores. This all means that it can be hard for a consumer to compare different kinds of systems.

In looking at the three primary water heater types described in this paper, the tankless units have the highest EFs (0.64–0.85), followed by the combination systems (0.51–0.83), and then the storage units (0.48-0.65). These efficiency ratings cover a large range of sizes and flow output, so the prudent consumer would compare across similarly sized models.

The most recent national energy survey (EIA 2003) estimated annual expenditures for water heating in homes relying on natural gas at $194 for a household of 2.7 members ($213 for single-family homes with an average of 2.8 household members). Since the vast majority of installed gas water heaters contributing to these cost estimates are tank-type, $194 is conservative (perhaps low) estimate of the annual operating cost for a tank-type heater. The highest efficiency storage unit would save approximately 10% relative to a unit of minimum efficiency, or $20 in annual operating costs. Where a tankless unit can be installed in place of a tank-type unit, 30% to 50% could be saved, for an annual savings of at least $60. Thorne (1998) estimated that a water heater combination system could save 36-39% on water heating ($72/year) and 10% on space heating ($53/year) for a total annual savings over separate, minimum efficiency equipment of $125.

Product Availability

Storage water heaters are by far the easiest for consumers to obtain, particularly when an immediate replacement is needed. Plumbers are most familiar with tank-type heaters and are likely to have storage heaters in stock and ready to install. There are approximately 100 unique models[2] available from a total of 11 different manufacturers (GAMA 2004a). In contrast, there are just three manufacturers of tankless water heaters distributed in the United States, each with about 4 unique models. The problem of finding a plumber with the necessary experience with tankless units has been cited in press comparing tankless to storage water heaters. Anecdotal evidence indicates that for some people, finding units and plumbers to install them can be

[2] Unique models were determined by eliminating duplicate models that had the exact same first hour rating, energy factor, volume, input, and recovery efficiency.

difficult while others have no trouble with the purchase or installation. There are likely regional variations in availability and contractor familiarity.

Combination systems are available from at least five manufacturers, offering approximately 38 unique models (GAMA 2004a). Since most combination systems rely on a standard boiler or standard water heater, the primary barrier for homeowners is finding a plumber who understands the auxiliary function, e.g., the water heating from the boiler. As systems using radiant heating and condensing equipment become more common, installers' familiarity with these products should accommodate the growth in demand for combination systems.

Product Costs

While finding average costs for equipment can be difficult, we have relied on a variety of sources to estimate consumer costs for each of the major product types discussed above.[3] Standard gas storage-type heaters range in retail price from $270 to $380, excluding installation, with more efficient units at the higher end of this range (DOE 2003b). Installation costs vary depending on complexity of the plumbing, but a reasonable average is $300, for a total installed cost for a high-efficiency unit of around $700. A unit that meets the minimum efficiency levels will be closer to $550, installed, representing the least expensive gas water heater available.

Tankless water heaters are listed with retail prices ranging from $550 to $1,100, with installation likely to add an additional several hundred dollars (Wyatt 2002). A product survey online in February, 2004, found products capable of 3-5 gallons per minute (11-19 l/min) had a retail price (excluding installation) of around $800. The assumed cost, then, for an installed, relatively high-flow tankless unit is $1100.

Combination systems are much more expensive than stand-alone water heaters, but by definition, they provide space heating, so any cost comparison must take this into account. Thorne, in a 1998 study, compared the costs of integrated systems with their conventional alternatives (separate water and space heaters). She found that a gas boiler with an integrated indirect-fired water heater cost $4,500 compared to the combined cost of $3,185 for a minimum efficiency gas boiler plus separate gas water heater. For a combination system relying on a powerful water heater, the relative costs were $3,500 for the combination system versus $2,235 for a minimum efficiency furnace and water heater.

Other Factors

While safety concerns such as scalding may have been a problem in the past with certain technologies, advanced controls have been added to prevent this. Reliability is difficult to predict or estimate since no national data are collected comparing different types of water heaters. Warranties, which can sometimes indicate a manufacturers' confidence in the reliability of its product, are available for all products, and typically range from three to ten years.

[3] Product costs vary significantly from region to region and precise calculations were not possible for this study. We have used what information we could find from DOE reports, articles on water heating, and anecdotal evidence. We have also tried to be conservative for both savings and cost calculations and to make clear any assumptions used so that readers can adjust comparisons based on local or updated price information.

Overall Program Considerations

Table 1, below, summarizes the factors likely to be most important to a program administrator for determining whether to promote a particular efficient technology. Each component is described in greater detail in the sections above. The relative importance of each aspect will depend on the specific goals of the program administrators and characteristics of the local market.

Table 1. Comparison Summary of Significant Characteristics of Residential Gas Water Heating Technologies

Technology	Storage	Tankless	Combination
Efficiency	EF 0.48–0.65	EF 0.64–0.85	EF 0.51–0.83
Advantages	familiarity and low first cost	most energy-efficient; space efficient	elegant solution where space and water heating needed
Limitations	higher EF often require larger tanks, may be space limitations; not a big jump in efficiency	limited flow appropriate for water-efficient homes; less familiar in market; expensive	expensive when not installing both water and space heating; may be hard to find service technicians
Availability	very common	limited manufacturers and models	equipment available but experienced installers may be hard to find
Installed Cost	$700 (50 gal, highest EF)	$1,100 (3-5 gal/minute, 11-19 l/min, flow)	$3,500 (water heater-based) $4,500 (boiler-based)
Incremental Cost	$150 (over minimum EF storage unit)	$550 (over minimum EF storage unit)	$1,300 (over minimum efficiency separate equipment)
Annual Savings	$20	$60	$125
Return on Investment	7.5%	9.1%	9.6%
Program Design Considerations	thin margins on these “commodities” leave little “room” for promotions	manufacturers may contribute to marketing expense, e.g., “co-promotion”	most often modular systems with several suppliers and several marketing budgets

Conclusions

While the vast majority of residential, gas water heaters sold and installed is still the storage-type, there are more efficient gas alternatives available today. While uncommon in the US market, some of these technologies are well-established in foreign markets. Early safety concerns associated with tankless water heaters have been addressed with advanced controls. Similarly, burner modulation has allowed for increased flows, making tankless units more applicable for larger households provided the house’s water end-uses are efficient. Combination systems, while relatively expensive upfront, can be cost-effective for new construction or major system retrofits.

Program administrators considering promoting alternative, efficient gas water heating technologies should study the local market within their service territory to assess whether adequate market infrastructure exists to support proposed programs. They may also consider the type of housing that they serve. For example, if there is a lot of new-home construction, they could focus on working with local builders to promote combination systems. After a complete situation analysis, the administrator should consider his or her energy saving objectives, relative to program timing and expense levels, and then target the markets and technologies where such objectives could be achieved. The authors also recommend that program administrators consider efforts of similar efficiency organizations that might offer an opportunity to leverage lessons learned or momentum on a particular front.

For example, if an administrator does the above analysis and determines that the primary barrier to increasing the sales of efficient products is the lack of contractor knowledge; programs could educate plumbers about installing and maintaining systems. The authors recommend that complementary educational efforts targeting homeowners accompany a training effort to provide the demand that can increase contractor participation. Knowledgeable contractors can then be enlisted to promote efficient products. A large-scale demonstration of tankless and combination systems might also convince influential builders of technological feasibility and available savings, providing a potential basis for differentiation of their homes in the marketplace.

Determining the most appropriate type of water heater for a home can be difficult. The decision will need to be based on consideration of the local market infrastructure, availability of different technologies, equipment and installation costs, the predicted water use in the home, and whether space heating and water heating can be integrated. What may be cost effective for one home may not be appropriate for another. Individual homeowners may value technology characteristics differently (e.g., one may focus more on operating costs while another is willing to pay more as long as he never runs out of hot water). These factors combine to make it challenging to design a program to promote efficient water heating, and efficiency programs don't want a customer to be unhappy with a water heater's operation or costs. Nevertheless, the authors believe that program administrators can research and consider all of the factors affecting their local water heating market and design programs that recognize the strengths and weaknesses of each type of efficient water heating technology.

Glossary

annual fuel utilization efficiency: a measure of the seasonal *fuel* efficiency of a furnace or boiler, equal to the heat energy transferred to the conditioned space divided by the fuel energy used; abbreviated AFUE.

combination water heater: a system that relies on one piece of equipment (typically a boiler or storage-type water heater) to provide space heating and water heating.

combined annual efficiency: a measure of the efficiency of a combination space- and water-heating system; abbreviated CAE; defined in ASHRAE Standard 124-1991

combined appliance annual fuel utilization efficiency: effective efficiency of a combined appliance in performing the function of space heating; can be compared to AFUE of a non-combination space heating appliance; abbreviated CA_{AFUE}.

combined appliance energy factor: effective efficiency of a combined appliance in performing the function of water heating; can be compared to EF of a non-combination water heating appliance; abbreviated CA_{EF}.

condensing equipment: combustion equipment that transfers so much heat from the burning fuel to the water (or air in the case of a furnace) that resultant combustion products are cool enough to cause the water vapor to condense; resulting condensate can be corrosive to vents or chimneys.

energy factor: a measure of the overall efficiency of a water heater based on the model's recovery efficiency, standby losses (through the jacket and fittings), and energy input; determined by DOE test procedure; abbreviated EF.

recovery efficiency: the ratio of energy absorbed by the water to energy consumed by the heater during the period that the water temperature is raised from inlet to final temperature.

site energy: energy (in various forms, e.g., electricity, natural gas, fuel oil) consumed at the point of use; as opposed to *source energy* which takes into account losses in transmission and generation processes.

storage water heater: a heater that maintains a tank of water at a preset temperature, replenishing and heating water as it is drawn out of the tank.

tankless water heater: equipment that heats water when there is hot water drawn from the system, water goes directly into the distribution system and is not stored; also called "on-demand" or "instantaneous."

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