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An energy and cost comparison of residential water heating technologies

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ABSTRACT

Water heating is a significant user of energy. Several studies have investigated the development of more efficient systems. The present study compares several commercially available options for water heating and compares them with the performance of a recently developed of a gas-fired heat pump water heating system. Comparisons of each technology are conducted using annual energy use and operating cost metrics. Payback period predictions for the gas and electric heat pumps are performed with the electric and non-condensing gas storage units as a base case. Electric and gas heat pumps, at total initial costs of $2,400, are estimated to require 3.6 and 3.1 year payback periods when compared to an electric storage unit, respectively, while a gas heat pump with a total initial cost of $2000 is estimated to require 2.3 years. For this study a gas heat pump cost of $2400 was assumed. Daily total draw cases for a gas heat pump of 243, 303 and 379 L compared to a non-condensing gas storage unit as the base case show payback periods of 4, 3.2 and 2.5 years, respectively. This analysis shows that electric and gas heat pump technologies offer significant energy use and operational cost savings compared to baseline water heating technologies with reasonable payback periods.

1. Introduction

Water heating is the second largest user of energy in households, accounting for up to 18% of total energy costs [5]. As a result, focus on the development of more efficient water heaters has increased over the past decade. More efficient water heater designs, like heat pump systems, are being developed to offer Energy Factors (*EF*) above current designs. The Energy Factor is a rating based on a representative daily energy usage test to allow for comparison between different water heating technologies. Direct heated systems are limited to Energy Factors of one or less and have been approaching this theoretical limit for some time. The Energy Factor is one of the criteria considered in the ENERGY STAR© rating of water heaters.

In 2015, manufacturers shipped 8.4 million storage water heater in the United States, of which 52% were gas storage units [2]. In 2009, only 12.5% of the water heaters shipped in the United States were ENERGY STAR© rated [16]. Increasing the number of units shipped that meet this rating criterion is important in reducing residential energy consumption. This is more likely to happen if there are more ENERGY STAR© rated water heaters available. The life expectancy of a water heater is 10–15 years [5], which makes increasing the availability and number of these products more pressing because the opportunity to replace these units is infrequent. To address this, two approaches should be taken. First, the number of already commercially proven and available ENERGY STAR© systems should be increased. Second, the development and commercialization of new ENERGY STAR© qualifying water heaters is needed. In combination, more energy efficient water heaters will be available to consumers and increase market share.

The present study considers both of the steps mentioned above. A survey is performed to determine the overall state and availability of ENERGY STAR© water heaters. Current water heater technologies are discussed. A recently developed gas-fired absorption heat pump water heater that offers *EF* values greater than one is also discussed. Energy and cost analyses are performed to evaluate the current state of water heaters from a consumer's perspective and the cost of a gas heat pump to allow for a reasonable payback period is estimated.

2. Prior work

The studies discussed in this section investigate the cost

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implications of changes to water heater insulation and parts, as well as the implementation of new water heater designs. Changes in designs to meet US Department of Energy (DOE) standards, and the implementation of heat pump, gas instantaneous or tankless, and condensing gas storage units are also discussed.

Lekov et al. [15] performed a study to estimate the energy savings potential and associated costs for water heaters driven by three different energy sources: a 190 L electric heated unit, a 150 L gas-fired unit, and a 120 L oil-fired unit. Baseline models with current technology and future models that incorporate new mandated features were assessed. Variation in future models included different thicknesses of water blown and HFC-245a blown insulation (to be used in place of HCFC-141b blown insulation), heat traps, plastic tanks, improved flue baffles, side arm heaters and several other potential improvements. The study showed that for the water heaters investigated, energy-efficiency can be increased by 4% for electric units, 9% for gas-fired units and 2% for oil fired units. The importance of the blowing agent and insulation thickness to reduce standby losses was highlighted. A payback period threshold of less than four years was used to determine acceptable designs. The study concluded that electric and gas-fired water heaters offer a much higher and cost-effective efficiency level with an acceptable payback than oil-fired units.

Tomlinson and Murphy [19] investigated the performance of 17 integrated electric heat pump water heaters installed at homes in the United States over a period of 18 months. Eleven of the units were installed in the South East Region. The units were equipped with electric resistance heaters for back up heating. Units were switched between heat pump and electric resistance heating to allow for comparison of operational performance. The average coefficient of performance (*COPs*) values in resistance and heat pump mode were calculated to be 0.86 and 2.00, respectively. Consumers experienced an average energy savings of 55% with a heat pump water heater. This shows that there is the potential for significant energy and monetary savings for an end user. Other important findings from this study were that hot water draw patterns varied significantly from 87 to more than 417 L per day, compressor runtimes were expectedly long (multiple hours and up to 11.5 h per day) and the use of the heat pump did not aggravate hot water run-outs as might be expected. They defined hot water run-outs as a draw that ended with a tank outlet temperature of 40.5 °C or lower. Run-outs were typically experienced less than 5 times a day and were not dependent on the mode of operation (resistance heater or heat pump).

Schoenbauer et al. [18] investigated the use of gas-fired storage water heaters, instantaneous water heaters, and condensing instantaneous water heaters for residential applications by performing field tests at ten households. The 15-month study showed that instantaneous water heaters allowed for a reduction in energy use and operational cost when compared to the standard gas-fired storage unit. Non-condensing instantaneous units used 22–54% less energy than the storage units. Condensing instantaneous units used 23–63% less energy than storage units. However, the high installation cost, in addition to a lengthy payback period, makes the instantaneous units economically undesirable.

Lekov et al. [14] conducted a life-cycle cost and payback period analysis for gas and electric storage water heaters. The study was motivated by new energy efficiency standards for residential water heaters by the US Department of Energy set to take effect in 2015. Gas storage (condensing and non-condensing), electric storage and electric heat pump storage water heaters were assessed. Capital, installation and operational costs were considered for each unit. The study showed that efficiency improvements to the baseline units reduce the life-cycle cost in most cases for gas and electric water heaters. They found that electric heat pump and condensing gas units provided lower life-cycle cost for homes with large volume water heaters.

The studies discussed above highlight different aspects of different water heating technologies. Some valuable findings about heat pump water heaters were reported. The first is that the use of a heat pump did not result in hot water run-outs as is a concern of many evaluating the viability of this technology. The second is that the high-efficiency units are most suited for homes with large volume water heaters where they provide lower life cycle costs.

3. Rating systems

Several rating systems have been instituted to allow for the evaluation and comparison of different water heater designs on an equivalent basis. The Energy Factor allows for comparison of performance across all designs and is a U.S. Department of Energy test that evaluates energy usage throughout a representative day. Test conditions, instrumentation, installation, test procedure and calculation requirements can be found at DoE [4].

Technology-specific ratings have also been developed, and include the First-Hour Rating (*FHR)* for storage water heaters, and the Liters-per-Minute (*LPM)* flow rating for instantaneous water heaters. The *FHR* is the maximum volume of hot water that a storage water tank can supply within an hour where the tank is initially fully heated. The *LPM* is the maximum flow rate that can be provided by an instantaneous water heater while maintaining a temperature rise of 43 °C [6]. The U.S. Department of Energy uses these tests to benchmark technologies. The *EF* and other tests are used to set lower limits to the ENERGY STAR© rating. These values have increased and continue to increase as technologies are improved. For electric storage units, a minimum *EF* and *FHR* of 2.0 and 189 L per hour are required, respectively. For gas storage units, a minimum *EF* and *FHR* of 0.67 and 254 L per hour are required, respectively. For gas instantaneous units, a minimum *EF* of 0.82 and *LPM* of 9.5 L per minute are required.

Another aspect relevant to the comparison of fossil fuel and electric heated units is the accounting of the inefficiencies related to the generation and transmission of electricity. When accounting for these inefficiencies, the word Primary is typically used as a prefix for the variable of interest, e.g., Primary *EF*. The penalty associated with this added cost for grid electricity is a factor of 3.14 [3]. Similarly, source penalties associated with natural gas, propane and heating oil No. 2 are 1.05, 1.01 and 1.01, respectively.

4. Water heater designs

Water heating technologies investigated in the present study are briefly described here, along with their advantages and limitations. The majority of these technologies are commercially available and information on them was gathered from nationwide distributors [10], manufacturers (Rheem, Electrolux, Westinghouse), and energy related agencies [1,6]. Gas storage (non-condensing, condensing and heat pump), electric storage (direct heated and heat pump), tankless (non-condensing, condensing and electric) and heating oil water heaters are reviewed below. Figs. 1 and 2 show schematics of the water heating technologies under consideration here.

4.1. Gas storage

These systems use the combustion of natural gas or liquid propane to directly heat stored water. Natural gas systems are more common in areas with local natural gas utilities. Propane systems are more common in areas where on-site gas storage is required. The combustion of gas to heat water is simple, effective and