NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Comparison of Advanced Residential Water Heating Technologies in the United States

Jeff Maguire, Xia Fang*, and Eric Wilson
National Renewable Energy Laboratory

*Current Affiliation: Group 14 Engineering

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-55475
May 2013

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

Comparison of Advanced Residential Water Heating Technologies in the United States

Jeff Maguire, Xia Fang*, and Eric Wilson

National Renewable Energy Laboratory

Prepared under Task No. BE12.0102

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5500-55475
May 2013

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Acknowledgments

The authors thank the entire residential buildings team at NREL for their help with this work. The authors are particularly grateful to Jay Burch, Tim Merrigan, Kate Hudon, and Bethany Sparn of the National Renewable Energy Laboratory and Moncef Krarti of the University of Colorado Boulder for their review and other contributions. The authors also thank William Healey of NIST for providing some of the data on gas water heaters used here.

Executive Summary

A comparison of the most common residential water heating technologies was performed to determine what the most energy-efficient and cost-effective water heating technologies are when subjected to a variety of typical operating conditions. To perform this comparison, TRNSYS models of different water heaters were used to determine what the energy consumption of each water heating technology would be. Several available models were used and new models of condensing and heat pump water heaters (HPWHs) were created specifically for this work. Gas storage, gas tankless, condensing storage, electric storage, heat pump, and solar water heaters were simulated in several climates across the United States, installed in conditioned and unconditioned spaces, and subjected to low, medium, and high use draw profiles.

In each case modeled here, the whole house was simulated along with the water heater to capture any interactions between the water heater and the space conditioning equipment. Home models were based on Building America Benchmark homes to reflect typical new construction homes and varied based on location to reflect local building practices. Six locations, each representing a Building America climate zone, were chosen. Space heating equipment was chosen such that homes with gas water heaters used gas for space heating and those with electric water heaters used electricity for space heating. Thus, gas and electric water heaters are not directly compared here. However, all energy comparisons were done on a source energy basis to capture the differences in primary energy consumption associated with these fuel types.

For gas water heaters, solar water heaters typically used the least amount of source energy (see Table ES-1). Tankless water heaters were more efficient in lower use cases in cooling-dominated climates when the water heaters were in conditioned spaces because of their net impact on the space heating and cooling equipment. The tank losses in low use cases in cooling-dominated climates led to increased cooling energy consumption and higher source energy consumption. A condensing water heater came within 10% of being the most energy-efficient option for the high use case in Seattle with the water heater in conditioned space. This was due to the low solar resource, the high efficiency of the condensing water heater, and the net benefit of the condensing water heater tank losses.

Table ES-1. Gas Water Heating Option With the Lowest Source Energy Use

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Seattle	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Atlanta	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Los Angeles	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Houston	Tankless	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Phoenix	Tankless	Tankless	Solar Gas	Solar Gas	Solar Gas	Solar Gas

Yellow denotes no option is within 10% of saving the same amount of source energy and green denotes one other option within 10%

For electric water heaters, solar was usually the most efficient technology (see Table ES-2). However, HPWHs were the most energy-efficient technology in several scenarios. Typically, HPWHs provided higher energy savings than solar water heaters in the higher use cases in conditioned spaces in colder climates. In these cases, the HPWHs got a performance increase from the warmer ambient air temperature in conditioned space which is larger than the space heating penalty imposed by the HPWH. The solar resource in these locations is also relatively low, so HPWHs used slightly less energy than solar water heaters. In Seattle the solar resource is small enough that HPWHs could save slightly more energy than solar water heaters in unconditioned spaces. HPWHs also saved energy over solar water heaters in conditioned spaces in Houston and Phoenix because of the space conditioning benefit. HPWHs came within 10% of using the same amount of energy as solar water heaters in many cases, especially in Phoenix and Los Angeles.

Table ES-2. Electric Water Heating Option With the Lowest Source Energy Use

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Solar Electric	Solar Electric	HPWH	Solar Electric	Solar Electric	Solar Electric
Seattle	Solar Electric	HPWH	HPWH	Solar Electric	HPWH	HPWH
Atlanta	Solar Electric	Solar Electric	HPWH	Solar Electric	Solar Electric	Solar Electric
Los Angeles	Solar Electric	Solar Electric	Solar Electric	Solar Electric	Solar Electric	Solar Electric
Houston	Solar Electric	HPWH	HPWH	Solar Electric	Solar Electric	Solar Electric
Phoenix	Solar Electric	HPWH	HPWH	Solar Electric	Solar Electric	Solar Electric

Yellow denotes no option is within 10% of using the same amount of source energy and green denotes one other option within 10%.

A life cycle cost (LCC) analysis was performed to compare cost effectiveness of the various water heating technologies. The LCC analysis takes into account the net installed cost of each technology, the value of all energy used by a water heater over its entire life, and any maintenance costs. This analysis was performed using average installed costs in new construction and retrofit cases (where a gas or electric storage water heater recently failed and needed to be replaced), although the same building model was used for both scenarios. Cases with and without incentives were analyzed to determine the impacts of current incentives on the cost effectiveness of each technology.

For new construction homes with no incentives and gas water heating, tankless water heaters were often the most cost effective options (see Table ES-3). However, in most such cases, typical gas storage water heaters were within 10% of being the most cost effective. Tankless water heaters were also the most cost effective options in locations with high gas prices, such as Atlanta and Phoenix. Tankless water heaters also have low tank losses, so they are cost effective in unconditioned spaces in colder climates and in conditioned spaces in warmer climates. In some high-use cases, condensing water heaters were also within 10% of being the most cost-effective options. Although condensing water heaters used slightly less energy than tankless water heaters in some high-use cases, the condensing water heaters' higher installed costs prevented them from being the lowest LCC options. Solar water heaters never came close to being cost effective because of their high installed costs.

Table ES-3. Lowest LCC Gas Water Heating Option for New Construction Homes With No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Seattle	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Atlanta	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Los Angeles	Tankless	Tankless	Tankless	Tankless	Tankless	Gas Storage
Houston	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Phoenix	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

For new construction homes with no incentives and electric water heating, HPWHs often have lower LCCs than electric storage water heaters (see Table ES-4). They generally do better with higher use because the savings potential is higher when more hot water is used, but in many cases work out even at low use depending on local electricity rates. In most cases, the savings were so significant that the base case of an electric storage water heater was not within 10% of the LCC of a HPWH. In no case was a solar water heater close to being cost effective without incentives.

Table ES-4. Lowest LCC Electric Water Heating Option for New Construction Homes with No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	HPWH	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Retrofit situations differ somewhat from new construction cases. For gas water heaters, gas storage is always the most cost-effective option (see Table ES-5). For natural draft gas storage water heaters, a significant portion of the installation cost in new construction comes from the venting, so it is much cheaper to install a gas water heater in a retrofit than in a new home. HPWHs continue to remain cost effective in most cases compared to other electric water heaters (see Table ES-6). In retrofits, HPWHs have additional costs associated with space constraints because a HPWH is larger than a typical electric resistance water heater and because a louvered door may need to be installed to provide sufficient airflow around the water heater in cases where it is installed in a small space. These additional costs may make HPWHs less attractive in some cases, such as at low use in conditioned space in Phoenix. However, HPWHs remain the most cost-effective options in most cases.

Table ES-5. Lowest LCC Gas Water Heating Option for Retrofit Homes With No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Seattle	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Atlanta	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Los Angeles	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Houston	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Phoenix	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Table ES-6. Lowest LCC Electric Water Heating Option for Retrofit Homes with No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	Electric Storage	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Based on the LCC analysis, tankless water heaters have the potential to provide savings to homeowners in many new construction cases, but there is no cost-effective gas water heating upgrade option for retrofit homes because efficient gas technologies have higher installed costs in retrofit homes. For electric water heaters, HPWHs show significant potential to provide energy and cost savings to most homeowners. When incentives are also considered, solar water heaters become cost effective in some situations where there are significant local incentives.

Contents

List of Figures

Unless otherwise noted, all figures were created by Jeff Maguire/NREL

List of Tables

Unless otherwise noted, all tables were created by Jeff Maguire/NREL

Symbols and Abbreviations

ASHP	Air source heat pump
COP	Coefficient of performance
$Cost_{base}$	Base case capital cost
$Cost_{E}$	Energy cost
$Cost_{breakeve}$	Breakeven cost
c_p	Specific heat
d	Discount rate
DHW	Domestic hot water
DHWESG	Domestic Hot Water Event Schedule Generator
DOE	U.S. Department of Energy
E	Energy
E_{cons}	Consumed energy
E_{cool}	Cooling energy consumption
E_{del}	Delivered energy
E_{fan}	Fan energy consumption
E_{heat}	Heating energy consumption
E_{nrmlz}	Normalization energy
E_{par}	Parasitic energy consumption
E_{WH}	Water heater energy consumption
$E_{WH,net}$	Net water heater energy consumption
EF	Energy factor
HPF	Heat pump fraction
HPWH	Heat pump water heater
I	Investment cost
LCC	Life cycle cost
MC_{WH}	Water heater maintenance costs
m	Mass of water drawn
n	Length of economic study
OC_{base}	Base case operating costs
OC_{WH}	Water heater operating costs
OM&R	Operating, maintenance, and repair costs

PVC	Polyvinyl chloride
$\dot{Q}$	Rate of heat transfer
Q_{hp}	Heat transferred by the heat pump
Repl	Replacement cost
Res	Residual value
SEF	Solar energy factor
SPV	Single present value
t	Time
T	Temperature
T_{amb}	Ambient temperature
T_{out}	Outlet temperature
T_{req}	Required outlet temperature
T_{wb}	Wet bulb temperature
TE	Thermal efficiency
UA	Overall heat loss coefficient
UPV	Uniform present value
V_{out}	Outlet velocity
W	Water costs
w_{amb}	Ambient humidity ratio
w_{out}	Outlet humidity ratio
WH	Water heater
y	Expected water heater lifetime
η	Efficiency

1 Introduction and U.S. Market Factors

1.1 Introduction

Water heating is the second-largest energy use in U.S. homes after space conditioning (1), accounting for 20% of the total energy consumed, or 2.12 quads annually. Most U.S. homes use either natural gas or electric storage water heaters (2), but many higher efficiency water heating options are available. These include tankless water heaters, condensing storage water heaters, heat pump water heaters (HPWHs), and solar water heaters. All these technologies could provide energy savings to homeowners. Because water heaters usually have fairly short life spans, these technologies are often considered as ways to reduce energy consumption in retrofit situations. However, these units are more complicated than conventional gas or electric storage water heaters, which may limit market adoption. Many factors, especially mains temperature, the location of the water heaters in the homes, and the daily draw volumes and profiles impact the actual annual efficiency of these units.

A standard test (the Energy Factor [EF] test) is used to rate the efficiency of U.S. residential water heaters (3). This test consist of six draws with a total draw volume of 64.3 gallons evenly spaced over 6 hours and a 19-hour standby period when no water is drawn with a set inlet water temperature and ambient air temperature. This test allows the efficiencies of different water heaters to be compared to each other, but a water heater's actual performance and efficiency change with draw profiles, ambient air temperatures, and mains water temperatures. Thus, the rated EF is not the efficiency under all conditions, but provides the efficiency under a specified set of conditions. The actual in-use efficiency can vary significantly from the rated efficiency because actual conditions vary.

Detailed, validated models of these water heaters were used to provide insight into the actual annual efficiency and the impact of the aforementioned factors on their annual energy consumption. Every water heater was modeled in conditioned and unconditioned spaces to capture interactions—which may be significant—between the water heater and the space conditioning equipment. These results can be used to help homeowners choose the most efficient options for their particular situations. In addition to determining the most energy-efficient option, the most cost-effective option was also determined for each situation by calculating the life cycle cost (LCC) and breakeven cost of each unit.

The technologies covered here (typical gas storage, typical electric resistance storage, tankless noncondensing gas, HPWH, condensing storage, and solar with both gas and electric backup) represent many of the most common efficiency upgrades; however, several technologies are not covered here. These include electric tankless water heaters (central tankless and point of use "booster" tankless), high-efficiency noncondensing gas (such as power vent gas water heaters) higher efficiency electric storage water heaters (where the increase efficiency comes from lowered tank losses), a ground source heat pump with a desuperheater, hybrid tank-tankless water heaters, indirect water heaters, and condensing tankless water heaters. Tankless electric and high-efficiency gas and electric storage water heaters were not included because they represent only small potential savings with modest increases in efficiency over the base case. Ground source heat pumps with desuperheaters, hybrid water heaters, and indirect water heaters are also potential options. However, these are not common in the United States and were therefore excluded. Data about tankless condensing water heaters are lacking to create and validate a detailed model of this technology. Future work may provide the information necessary to create this model.

This report begins by discussing the current U.S. water heater market and providing an overview of these technologies. This is followed by a discussion of the models employed in this work as well as a more detailed discussion of the new models specifically created for this project. The details of the building models used in the whole-home annual simulations are then presented. Finally, the results of the whole-home simulations and the economic viability of each technology are discussed along with potential areas for future work.

1.2 Current U.S. Water Heating Market

The U.S. residential water heater market is dominated by storage type water heaters. Gas and electric storage water heaters made up about 94% of residential water heater shipments in 2009 (2). Gas tankless water heaters made up most of the remaining market (~5%); all other technologies comprised < 1% of shipments. Fifty-two percent of U.S. homes use natural gas as the primary fuel for water heating and 41% use electricity (4). The remaining homes use other fuel sources such as fuel oil, propane, wood, and solar. The distribution of water heater fuels varies by region as shown in Figure 1.

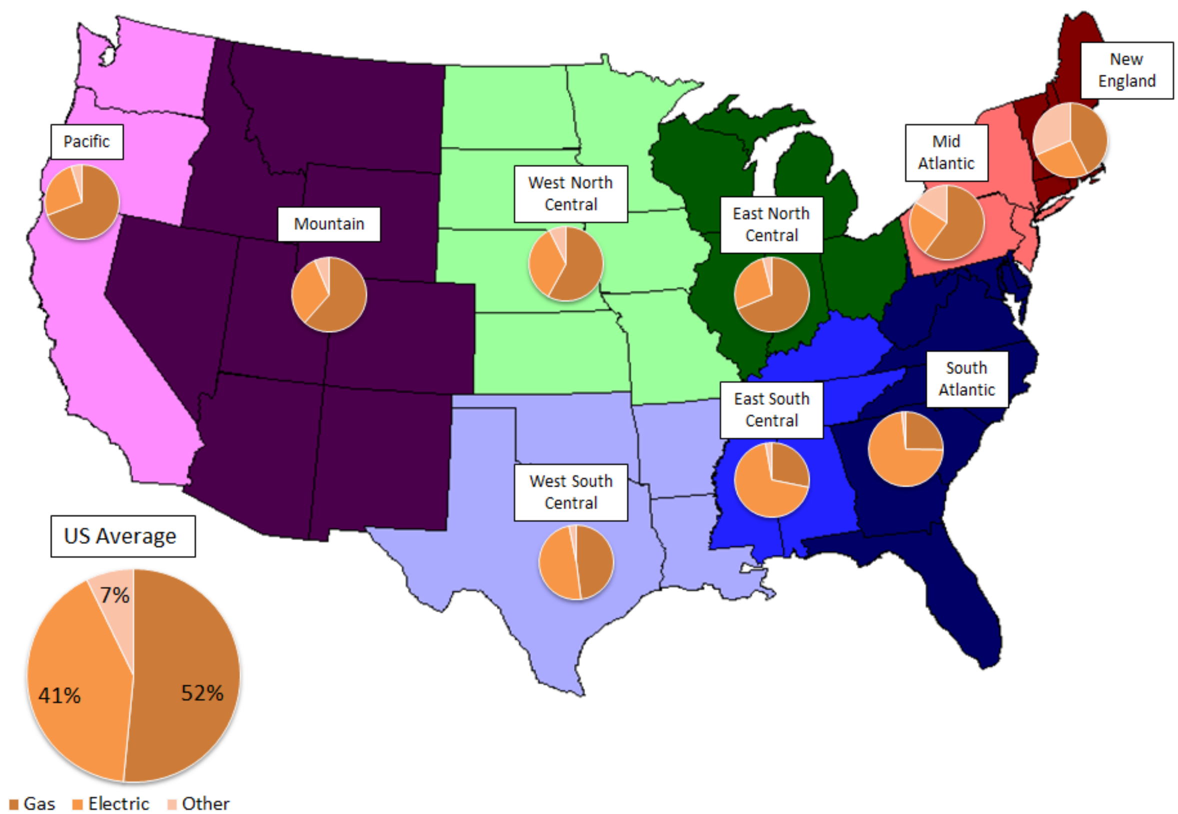

Figure 1. Distribution of fuel types for installed residential water heaters (4)

The ENERGY STAR® branding for water heater technologies plays a role in the U.S. market. ENERGY STAR-qualified units must meet certain energy efficiency requirements to be eligible for the branding. Consumers are very aware of the program: two thirds of households can recognize the ENERGY STAR label on sight, and more than three fourths of households have at least a general understanding of the label's purpose (5). Any purchased ENERGY STAR-qualified unit that is eligible for a tax credit provides an incentive for consumers to seek out this label. There are currently ENERGY STAR standards for all water heater technologies except electric storage and electric tankless units. The ENERGY STAR standards for condensing water heaters and HPWHs have been developed only in the last few years. There are currently incentives for ENERGY STAR-certified solar water heaters, although other ENERGY STAR-rated technologies have previously qualified for incentives. ENERGY STAR-certified units made up 13% of total water heater sales in 2010 (see Figure 2) (6).

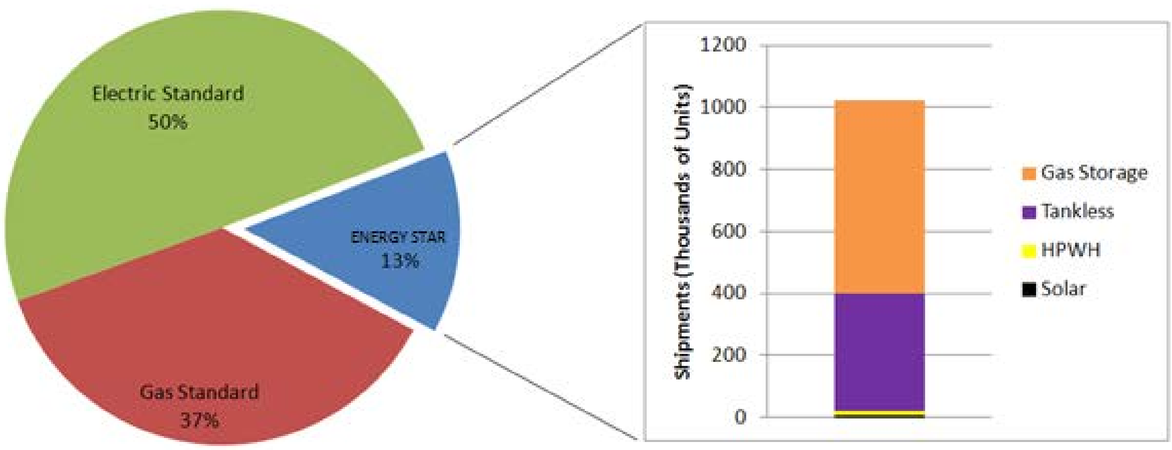

Figure 2. U.S. residential water heater sales in 2010 by technology (2)

The next U.S. energy efficiency standards for residential water heaters will require gas and electric storage tanks with a capacity > 55 gallons to use either condensing (for gas) or HPWH (for electric) technologies (7). The new standard will go into effect in 2015, and could lead to a wide adoption of energy-efficient water heaters.

1.3 Market Barriers for Efficient Water Heating Technologies

The largest market barrier for energy-efficient water heaters for residential applications is the high first cost. A highly efficient water heater can cost several times more than a comparable less efficient system (see Table 1).The approximate installed cost range provided in Table 1 covers new construction and retrofit scenarios. The energy savings from a more efficient water heater can offset the higher first cost over its lifetime, but that does not always provide a strong enough incentive. This is particularly true if a water heater is installed for someone other than the occupant, such as the owner of a rental property, who typically would see no benefit from the energy savings provided by the more efficient system when utility bills are not included in rental fees. Poor customer awareness and a lack of trained installers for some water heating technologies are also common barriers (8). In retrofit situations, additional work, such as installing a larger gas line or a new electric circuit, may be required for a new technology, increasing the installation cost. Finally, the often immediate need for a new water heater can be a serious obstacle to the adoption of energy-efficient technologies. Thirty percent of all water heaters are purchased because the previous unit has failed catastrophically (6); a customer rarely performs an extensive search for an efficient water heater in this case and instead takes whatever is "on the truck."

Table 1. Comparison of Costs, Rated Efficiencies, and Lifetimes of Various Water Heating Technologies (9) (10)

Residential Water Heating Technology	Approximate Installed Cost ($)	Average Lifetime (years)	EF	Source Efficiency
Gas Storage	700–1,900	13	0.58	0.53
Gas Tankless*	1,900–2,900	20	0.82–0.98	0.75–0.90
Gas Condensing Storage	1,500–2,400	13	0.70–0.85**	0.64–0.77
Solar With Gas Backup	6,000–14,000	30	1.20–6.00***	1.10–5.49
Electric Storage	400–800	13	0.90	0.27
HPWH	1,200–2,200	13	2.00–2.35	0.59–0.70
Solar With Electric Backup	6,000–14,000	30	1.80–9.00***	0.53–2.67

* Costs are for noncondensing units

** Estimated EF based on thermal efficiency (TE) and laboratory test results from (11)

*** Solar energy factor (SEF), based on a range of solar fractions of 0.5–0.9

Two efficiency metrics are provided in Table 1, the rated efficiency (EF or SEF) and the source efficiency. The rated efficiency is based on site energy consumption (natural gas or electricity consumed at a home); the source efficiency takes into account all the primary energy that is consumed to provide electricity or natural gas to a home. To calculate the source efficiency of these units, national average site-to-source ratios of 1.092 for natural gas and 3.365 for electricity were used (12). Although electric water heaters are generally more efficient in terms of site energy consumption, gas water heaters are much more efficient on a source energy basis because natural gas has a lower site-to-source energy ratio.

The largest market barrier for gas tankless water heaters—especially condensing ones—is their high first costs. However, they have had the highest market penetration of any of the high-efficiency technologies discussed here, with 380,000 units shipped in 2009 (2). In retrofit situations, the larger burner of a tankless water heater may require that a larger gas line and vents be installed, which contributes to the high first costs shown in Table 1. Regular maintenance may need to be performed to remove scale buildup from inside the heat exchanger, particularly in areas with hard water. There is some disagreement about how serious this issue is (13), however, and whether such maintenance will be necessary in many homes.

For condensing water heaters, the high first cost largely comes from the more expensive materials required in the heat exchanger for the flue gas, which must have high corrosion resistance (8). Recently manufacturers of condensing water heaters have had the high first cost in mind when designing the system. They have thus attempted to use parts from water heaters currently on the market and experimented with various materials for the heat exchanger. An ideal market for condensing water heaters is high-use residential applications (such as combined space and water heating applications) and light commercial applications, where the high first cost may be a smaller factor (14).

HPWHs have historically also seen poor market penetration, although they have been sporadically available for many years. The main reason for this is the high first cost. They can cost 2–3 times as much as a comparable electric storage water heater, which presents a significant barrier to market entry. HPWHs are also sometimes perceived to have reliability issues (15). This perception comes from experience with earlier generations of HPWHs, which had reliability and durability issues. Although the current generation of units has not yet shown any of the problems previous generations had, people who were aware of previous HPWH pilot programs may still be skeptical. Until recently, HPWHs were primarily made by small manufacturers, which led to high manufacturing costs; also, these manufacturers would not likely have been able to meet a large surge in demand. Several large manufacturers have entered the market and currently have ENERGY STAR-qualified HPWHs available. It is still unclear how large an impact these new units will have, as they have only been on the market for a few years.

In 2009, estimates for the sales of new solar water heaters are in the range of 7,000–40,000 units, making up < 0.1% of new water heater sales (2) (16). The largest market barrier for solar water heaters has been the high first costs. Table 1 shows that a solar water heater costs several times more than a gas storage water heater, even after federal tax credits are included. Solar water heaters also need to be roof mounted. This requires a roof that does not face north and is not heavily shaded, which further limits market penetration.

2 Strengths and Weaknesses of Water Heating Technologies

2.1 Gas Storage Water Heaters

Gas storage water heaters (see Figure 3) are the most common and least efficient type of gas water heater (minimum EF = 0.58 for a 50-gallon unit). This low efficiency is caused by two factors: the combustion efficiency of turning natural gas into heat and the tank losses. A large part of the low combustion efficiency is that typical gas water heaters need to vent the combustion products at a relatively high temperature. If the flue gas were allowed to cool to a temperature where the water vapor condenses out of the flow, the sulfur odorizer added for safety reasons could combine with the condensed water to make sulfuric acid, corroding the flue and destroying the water heater.

Because most gas storage water heaters have central flues, they have higher tank losses than electric storage water heaters. This is most clearly evidenced by the difference in a gas water heater's recovery efficiency and the rated EF. A typical gas water heater has a recovery efficiency of about 76% and an EF of about 0.6. An electric resistance water heater has a recovery efficiency of about 99% and an EF of about 0.9. Convection loops can form in this flue, further increasing the heat loss. Higher efficiency designs such as power venting water heaters reduce this loss through the central flue, but these units are more expensive. High-efficiency noncondensing gas storage water heaters are not considered in this work, as they represent only an incremental improvement in this technology.

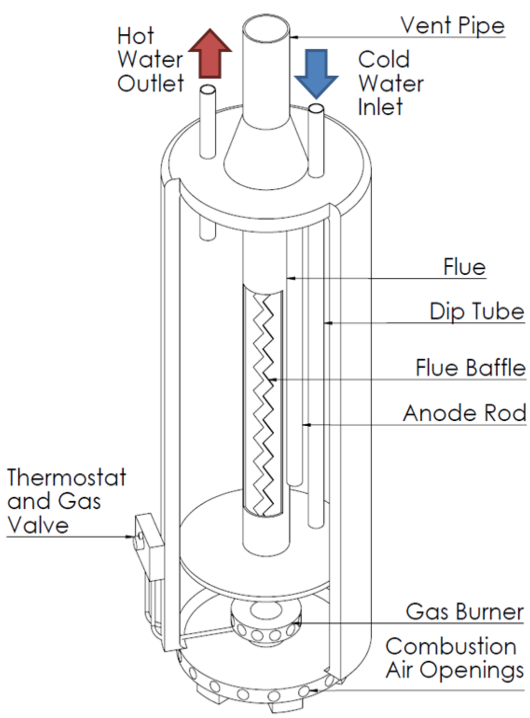

Figure 3. Gas storage water heater

2.2 Gas Tankless Water Heaters

Gas tankless water heaters (see Figure 4) improve on the efficiency of gas storage water heaters by removing the standby losses during times where no hot water is drawn. Typical gas tankless water heaters can therefore achieve much higher rated efficiencies (EF = 0.82) than noncondensing gas storage water heaters. The efficiency of a tankless water heater is very sensitive to the draw profile. Because of differences in the EF draw profile (which consists of 6 large draws) and typical domestic hot water (DHW) use (which is made up of many small draws), the actual in-use efficiency is often lower than this rated efficiency (17), because there are cycling losses between draws. A tankless water heater also requires a minimum flow rate before the gas burner will fire. Additionally, once a draw begins and the burner fires, both the water and the heat exchanger have to come up to the set point temperature. As a result, during each draw there are losses associated with bringing the heat exchanger up to temperature. These losses can be significant if a homeowner uses hot water with many short draws spread out over a day.

One other issue associated with tankless water heaters is the "cold water sandwich" that commonly occurs between two closely spaced hot water draws (for example, two morning showers). After the first draw, there may still be hot water in the pipes but the tankless water heater will have turned itself off because no water is being drawn. The second event will start with hot water from the pipes, but will be followed by a slug of cold water right before the burner ignites and then by hot water once the water heater fully fires. This is primarily a comfort issue and does not significantly impact efficiency. It can be avoided by installing a small buffer tank or using a specific control strategy designed to solve the problem. Although the cold water sandwich has historically been an issue, some newer units use mitigating control strategies.

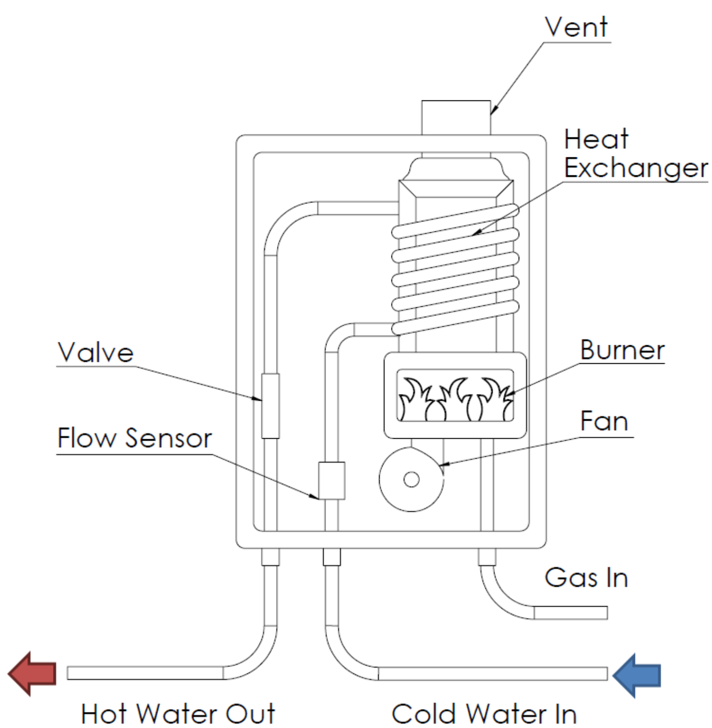

Figure 4. Tankless water heater

2.3 Condensing Storage Water Heaters

Condensing storage water heaters (see Figure 5) improve on typical gas storage water heaters by allowing the flue gas to condense before it is vented. This condensation allows the latent heat of the water vapor to be captured, significantly increasing efficiency (EF ≈ 0.80). This design typically uses a power vented design with a helical heat exchanger in the center of the tank instead of the central flue to reduce standby losses. A corrosion-resistant heat exchanger is required to avoid corrosion issues associated with the acidic condensate. This heat exchanger is typically made of either glass lined or stainless steel and is a substantial additional cost. These units are also not currently in high demand and the lower production volume leads to higher manufacturing costs. However, it vents at low temperatures, so lower cost polyvinyl chloride (PVC) can be used for the venting instead of metal in some new construction installations (18). The power vented design also allows for side venting, which can greatly reduce the required length of the exhaust vent. The lower installation cost from PVC side venting can help to offset the high first cost, which can help to make a condensing water heater cost competitive with a typical gas storage water heater in some new construction cases.

Although condensing water heaters are considerably more efficient than traditional gas storage water heaters, their combustion efficiency is not constant. Actual efficiency varies depending on the amount and rate of condensation in the heat exchanger, which is directly impacted by the surrounding water temperature and the part load (if the unit is capable of modulating). As with any storage technology, standby losses can significantly degrade the annual efficiency in low load applications.

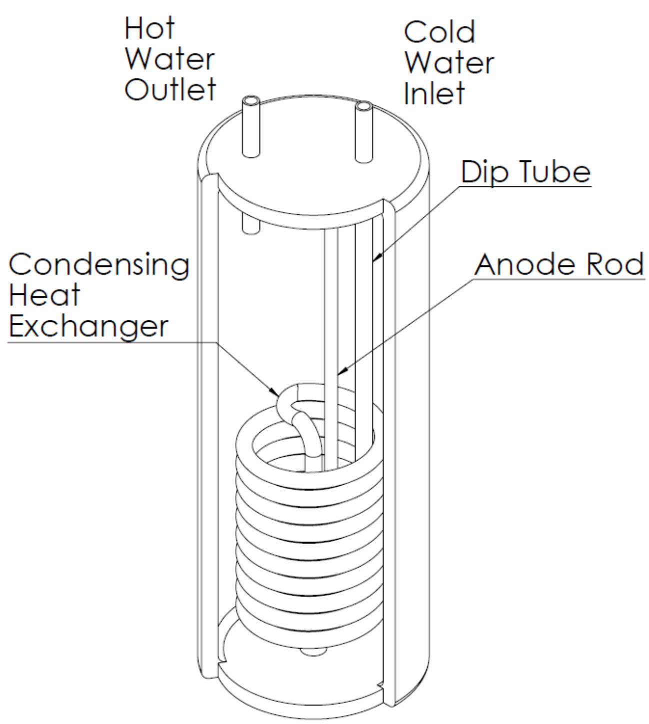

Figure 5. Condensing water heater

2.4 Electric Resistance Storage Water Heaters

Electric storage water heaters (see Figure 6) are the most common—and least efficient—electric water heating option. They are, however, more efficient (on a site energy basis) than gas storage water heaters (minimum EF = 0.90 for a 50-gallon unit). The conversion efficiency of an electric resistance heating element is very close to 1, so tank losses are the major source of inefficiency. Electric water heaters do not need a flue, which reduces their tank losses relative to a gas storage water heater. Most use two electric elements in a master-slave relationship; the upper element is the master, which meets the load in the fastest manner possible. Increasing the jacket insulation increases the efficiency of an electric storage tank water heater, but per-unit savings are modest. However, their national savings potential may be large if they were to be widely adopted (19).

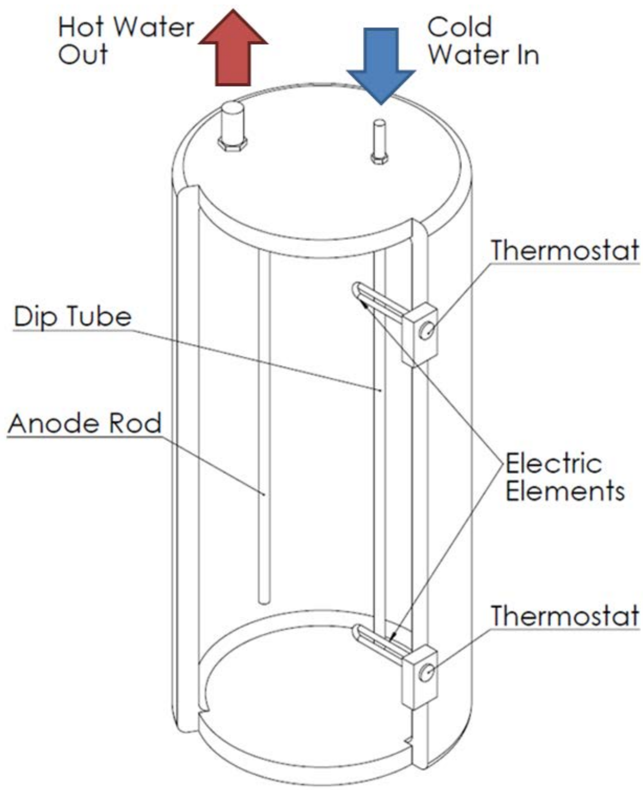

Figure 6. Electric resistance storage water heater

2.5 Heat Pump Water Heaters

HPWHs (see Figure 7) are much more efficient (EF = 2-2.5) than standard electric resistance water heaters. Most HPWHs in the United States are air source and operate by using a heat pump to remove heat from the ambient air and add it to the tank. However, other heat sources could be used (20). For a HPWH, the efficiency is typically measured and reported as a coefficient of performance (COP). The COP is defined as the amount of energy delivered by the unit divided by the amount of energy consumed. Two COPs can be defined for an integrated HPWH: the heat pump COP, which takes into account only the heat pump performance, and the system COP, which also takes into account the standby losses and electric element energy use. The EF rating is equivalent to the system COP for the specific conditions of the EF rating test. System COP is most typically measured and reported and is used to describe HPWH performance here. Typical system COPs for these units are around 2–3 internationally; rated EFs are typically 2–2.5 in the United States. HPWHs have long had a significant market share in Japan, where some HPWHs using carbon dioxide as the refrigerant can achieve a rated COP of 4 or higher under Japanese rating conditions (21).

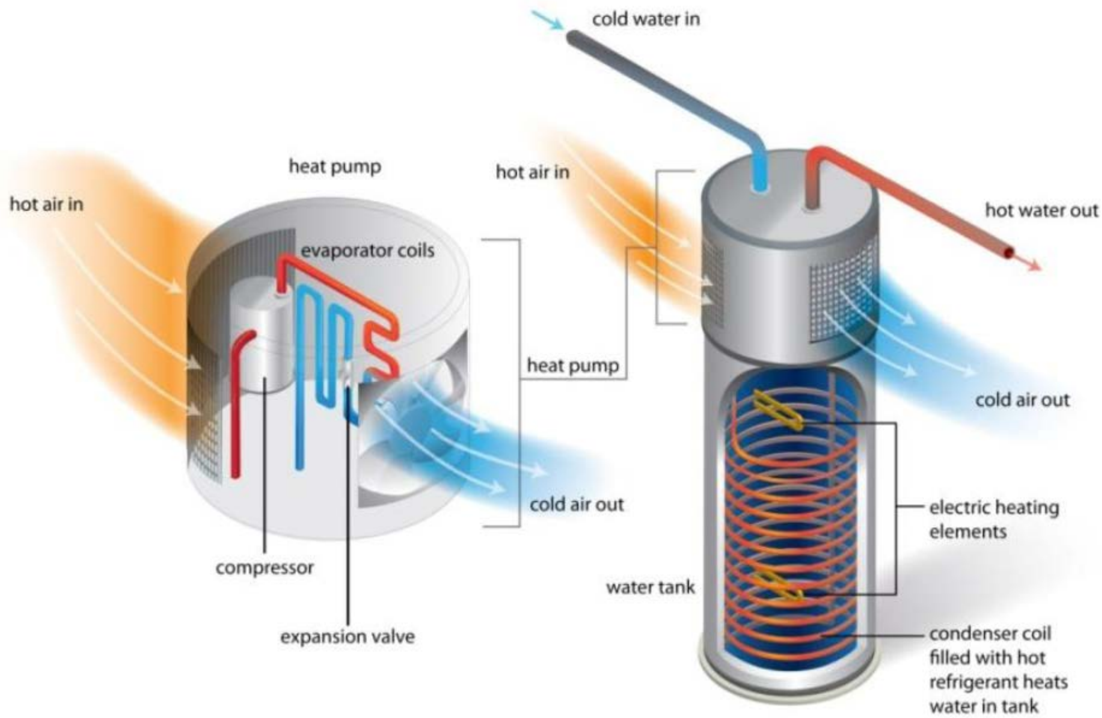

Figure 7. Heat pump water heater (22)

(Illustration by Marjorie Schott/NREL)

HPWHs typically feature both a heat pump and at least one electric resistance element for heating. The electric resistance element(s) usually turn on if the heat pump cannot keep up with the load or if the ambient air conditions prevent the heat pump from running. Each manufacturer has its own control logic (based on system design) for determining when to switch to the backup electric resistance element(s). How often these have to be used is heavily dependent on climate and hot water use. A "heat pump fraction (HPF)" metric, analogous to the solar fraction for solar water heaters, can be used to estimate performance. However, the HPF is usually not calculated in a way that takes into account potential interactions with the space conditioning equipment.

The heat pump COP depends heavily on the temperature of water adjacent to the condenser, ambient air temperature and humidity, setpoint temperature, hot water draw profile, and operating mode. All these factors can cause the actual efficiency of this unit to vary widely, particularly if it is in unconditioned space. This unit will cool and dehumidify the space it is in while the heat pump is running. This may increase the overall energy consumption of the building, particularly if the unit is installed in conditioned space in a heating-dominated climate. It must also be installed in an area with enough airflow or a large enough volume to ensure it does not recirculate the cooled exhaust air, which would cause the heat pump COP to decrease. In retrofit situations, this may require that a louvered door be installed if the water heater is in an enclosed closet. Ducting the HPWH is also a possibility, although many units currently available are not configured for ducting.

2.6 Solar Water Heaters

Solar water heaters offer an opportunity to greatly reduce gas or electricity consumption for hot water. They use the sun to heat water for DHW or hydronic space heating applications. Solar water heaters typically provide more than half the required energy for water heating; a backup system provides the remaining energy (23). The backup system could be any residential water heater, including a condensing or HPWH. Currently more than 100 models of solar water heaters are on the U.S. market (6).

Several types of collectors can be used for solar water heating. The two most common options are a flat plate collector and an evacuated tube collector, but some systems have the water storage integrated into the collector (these are commonly referred to as ICS, or integrated collector storage systems). Flat plate collectors for residential water heating applications consist of a collector surface that absorbs the solar radiation, a glazing to prevent the absorber from reradiating the solar energy, a heat transfer medium (for DHW applications, this is almost always water or a propylene glycol-based heat transfer fluid, depending on the climate and system type), and insulation on the sides and back to prevent losses by conduction and convection (24). Evacuated tube collectors consist of several absorber surfaces with heat transfer fluid flowing through them encased in a vacuum. The vacuum around the collector minimizes the losses to the environment from the collector, because it drastically reduces the conduction and convection losses. However, they are typically much more complicated, and can be more expensive, than flat plate collectors. ICS systems typically consist of absorber tubes with a large enough volume to also act as a storage tank. Because they are especially susceptible to freezing (25), they are typically only used in climates where the outdoor air temperature rarely falls below freezing.

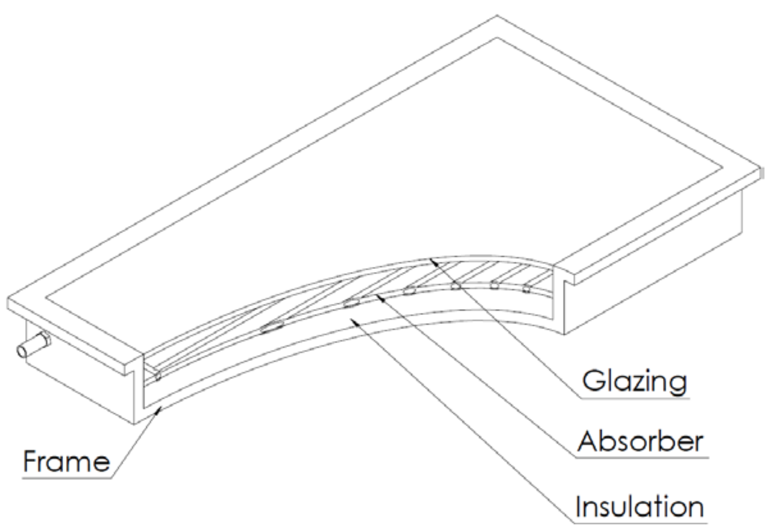

Figure 8. Typical flat plate collector

The decision about which collector type to use is usually specific to the application and the required water temperature (26). For the temperatures used in most residential applications, flat plate collectors are typically more efficient, although for higher temperature applications an evacuated tube collector may be more efficient. Flat plate collectors also make up 76% of the collector sales for U.S. DHW applications (27), and are therefore the only solar water heating technology considered here. Evacuated tube solar water heaters are typically better suited to commercial or light industrial applications.

Solar collectors in the United States are rated by the Solar Rating and Certification Corporation (SRCC), which tests collector designs under standardized conditions to characterize their thermal performance (28). The SRCC procedure takes data from standardized tests and predicts the daily amount of energy that will be captured by the panel depending on the weather and application. This test also produces an equation for the collector that provides the efficiency as a function of the inlet fluid parameter which is used in simulations to project energy savings for each solar water heater in a variety of locations. The SRCC also makes these data available for modeling solar water heaters.

3 Model Descriptions

Modeling was done using TRNSYS, a visual programming environment used for modeling transient systems, primarily thermal and electrical systems (29). TRNSYS has a modular structure that allows users to easily create their own models. However, most water heating technologies have already been modeled in the TRNSYS environment (29). Models for gas storage, electric storage, and solar water heaters have been available since the initial release of TRNSYS, although recently created models more accurately reflect the actual performance by capturing effects not included in the original models (30) (31). Accurate models of gas tankless water heaters have been recently created and verified (32). However, accurate models of a HPWH and a condensing water heater needed to be created for this work by modifying existing models in TRNSYS. A brief description of these models is included here; detailed descriptions of the older models and the new HPWH and condensing water heater models are provided in (33). Model parameters for each water heater are provided in Appendix A.

In addition to modeling the water heaters, a home was modeled in all cases to allow for the evaluation of the water heater's impact on the building's space heating and cooling energy consumption. Interactions with space loads could come from tank losses from the water heater or, in the case of a HPWH, heat being removed from the space and added to the storage tank. For a water heater in an unconditioned space, the building model is necessary to accurately predict the ambient air temperature and humidity for correctly calculating the tank losses, as well as the heat pump COP for HPWHs. A brief description of the home model is provided here and a more detailed description is provided in (33). Along with the home model, a detailed DHW draw profile from the Building America Domestic Hot Water Event Schedule Generator (DHWESG) (34) was used for all cases. The DHWESG and the draw profiles used for this study are described in detail below.

A summary table of the rated efficiency (EF, TE, or SEF, depending on the technology) and the nominal volume of each water heater simulated here is provided in Table 2. The EF is used as the rated efficiency for residential water heaters. The EF test subjects a water heater to a standardized series of draw profiles under a specific set of conditions. A modified version of the EF test is used to determine the SEF of a solar water heater. Some water heaters that are sold for residential applications are actually sized for commercial use and therefore have a rated TE instead of an EF. This is especially common with the condensing storage water heaters on the market today. The TE rating is based on continuous use of hot water and does not feature a standby period like the EF test. As a result, the TE is generally higher than the EF.

Table 2. Rated Efficiency and Volume of Each Water Heating Technology Considered Here

Residential Water Heating Technology	EF/[TE]/(SEF)	Nominal Tank Volume (gal)
Gas Storage	0.60	50
Electric Storage	0.91	50
Gas Tankless	0.82	–
Gas Condensing	[0.95]	50
Heat Pump	2.35	50
Solar With Electric Backup	(2.40)	80
Solar With Gas Backup	(1.30)	80

3.1 Gas and Electric Storage Water Heater Models

The gas and electric storage water heaters are modeled using a one-dimensional finite difference approach (33). The tank model consists of a vertical stack of isothermal nodes (see Figure 9). The gas and electric storage water heater models used here both use the same multinode storage tank model. Fifteen nodes are used here and are generally adequate for capturing the stratification in these types of water heaters (38). An overall heat transfer coefficient from the tank to ambient air is specified for each node to allow thermal shorts in the tank to be modeled at any location. A flue loss coefficient can also be specified to model the losses from the central flue in a gas water heater. Heat can be added to any node; the tank inlet and outlet can also be located in any node.

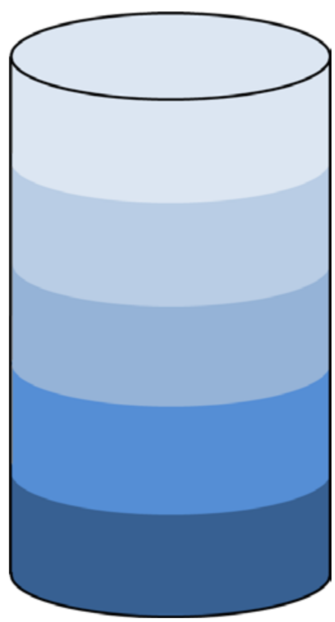

Figure 9. Stratified storage tank water heater model. Isothermal nodes are shown as varying colors.

For gas and electric water heaters sold in the United States, a fairly large margin of error is allowed in the actual volume compared to the nominal volume. The actual volume of a gas water heater has to be the nominal volume ±5%; for an electric water heater, it can be within ±10% of the nominal volume (35). Most manufacturers can produce tanks with much less variation in the actual volume than what is required and therefore tend to produce tanks with a volume at the low end of the specified range for cost reasons.

To accurately consider the impact of locating a gas water heater in conditioned space, the fraction of the heat loss that exits the flue instead of going to the surrounding space needs to be determined. An electromechanical flue damper can reduce the overall tank heat loss coefficient by one third for a 40-gallon gas water heater (9). Therefore, one third of the tank's heat loss is assumed to exit the flue and two thirds goes to the surrounding space. Because the actual amount of heat lost out the flue varies with many factors, including tank designs, ambient air temperature, and tank set point temperature, this is a rough estimate. The division for a 40-gallon gas water heater is assumed in all noncondensing gas water heaters modeled here because data on other sizes and configurations are lacking.

For the gas water heater, a standing pilot light was also modeled. This pilot had a power consumption of 450 Btu/h and the same combustion efficiency as the burner. Although the energy from the pilot light largely just offsets standby losses and does not significantly increase the energy consumption in many cases, which would make it unnecessary to explicitly model the pilot light, this is not true in all cases. Appendix B includes a discussion of the impact of the pilot light on overall energy consumption and the impact of including a pilot light in water heater models.

3.2 Tankless Water Heater Model

The multiple-node gas tankless water heater model used here was created based on and validated against extensive laboratory testing (32). The TRNSYS model used here has parameter values that are specific to the tankless water heater model used during laboratory testing. This particular unit was chosen for laboratory testing because it had the largest market share at the time and has a typical efficiency. The model subdivides the heat exchanger of the gas tankless water heater into multiple nodes and performs an energy balance on each node. This water heater can modulate gas flow into the unit to fire at the minimum rate necessary to meet the load.

The manufacturer of this tankless water heater provided the freeze protection algorithm used here; it was not validated by laboratory testing. The temperatures at the inlet and outlet are monitored to determine the likelihood of freezing. If either temperature drops below a threshold slightly above freezing, electric resistance heaters will turn on until the unit is heated to about 20°F above freezing. If the electric resistance heaters cannot keep the unit warm, the gas burner will fire to prevent freezing.

Data are lacking on how much of the heat lost from the tankless water heater exits the flue compared to how much goes to the surrounding space, so the same split that was used for gas storage water heaters (two thirds to the surrounding space, one third out the flue) was assumed for the tankless water heater to determine how much goes to ambient air as opposed to out the flue.

3.3 Heat Pump Water Heater Model

The new HPWH model developed here was based on an existing HPWH model (36), combined with the previously described stratified storage tank model. The model parameters were derived from extensive laboratory testing of residential HPWHs (37), and this model was based on the results from one of the five HPWHs tested. The existing model is a performance map-based model that defines the compressor power, total and sensible cooling, fan power and flow rate, and rate of heat rejection from the heat pump to the water as a function of water temperature, ambient air temperature, and ambient humidity. The existing model assumes that a fluid (typically water) is being pumped through the unit continuously from either the storage tank or the condenser and that all heat rejected by the unit goes into that fluid. The model also assumes that the HPWH has a single-speed fan.

The HPWH model used a similar performance map to the existing HPWH, but mapped the performance only to the wet bulb temperature and the tank temperature adjacent to the condenser instead of mapping to both dry bulb temperature and humidity. This modification was made because the laboratory testing did not fully explore the impact of humidity and primarily looked at the impact of wet bulb temperature. The performance map used here takes a list of points of the HPWH's performance at various water temperatures and ambient wet bulb temperatures and linearly interpolates between these points. The COP curves developed during laboratory testing for this HPWH were used to develop this performance map. A schematic of this model is shown in Figure 10. The performance map of COP as a function of water temperature and wet bulb temperature is shown in Figure 11.

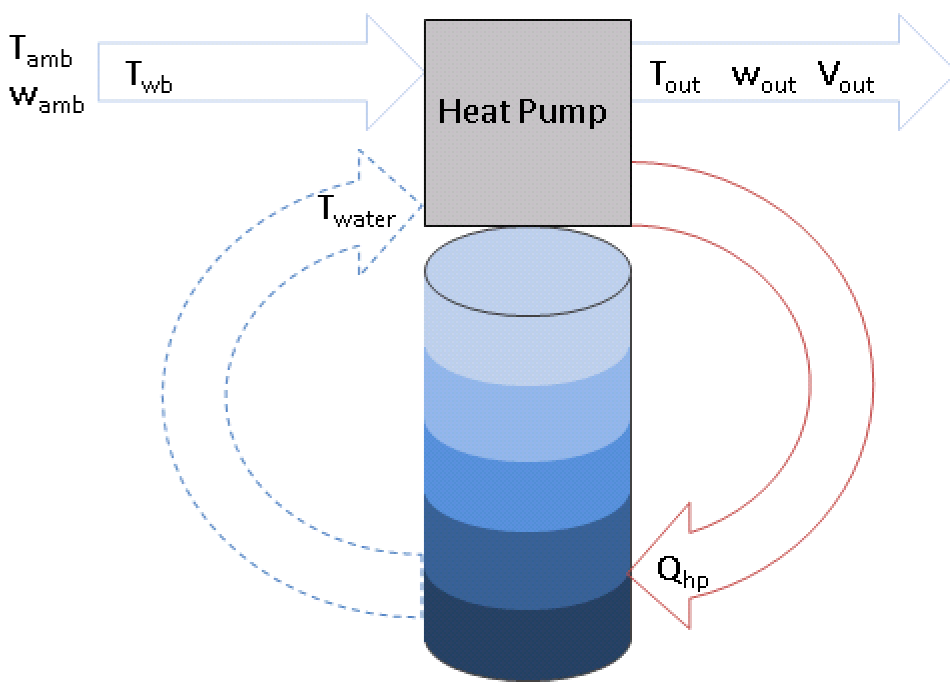

Figure 10. Schematic of the HPWH model

In Figure 10,

Q_{HP}	=	the heat added to the tank by the heat pump,
T_{amb}	=	the ambient (inlet) air temperature,
T_{out}	=	the outlet air temperature,
T_{wb}	=	the ambient (inlet) wet bulb temperature,
V_{out}	=	the outlet air flow rate,
w_{amb}	=	the ambient (inlet) humidity ratio, and
w_{out}	=	outlet air humidity ratio.

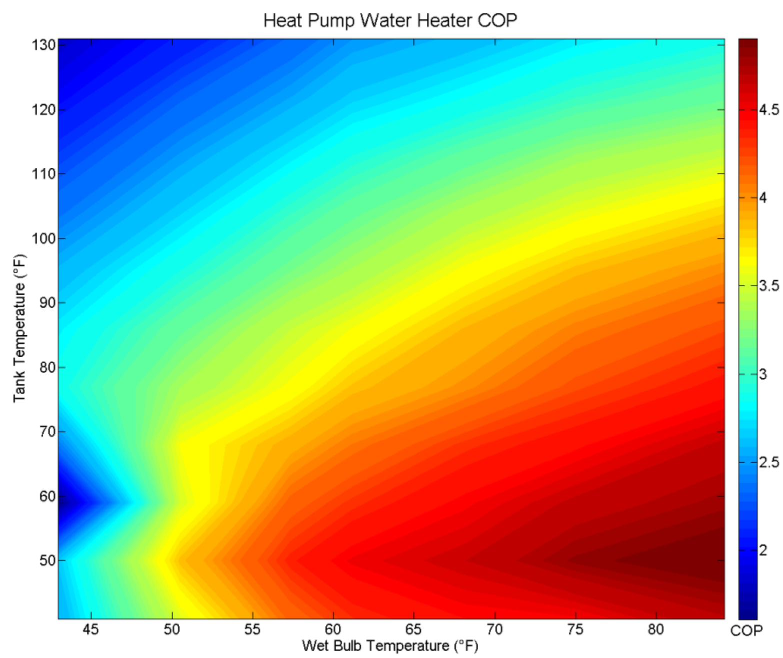

Figure 11. HPWH COP performance map

The HPWH on which the model is based is a 50-gallon unit with two backup electric resistance elements. The heat pump has a much lower capacity than the electric resistance elements, so if the heat pump cannot keep up with demand, the electric resistance elements will turn on. Control logic specific to the default operating mode of a tested unit was used to capture when the heat pump will turn on and when the unit will switch from the heat pump to the resistance elements. The model was able to capture the energy consumed by the HPWH to within 2% compared to laboratory testing of a day of simulated hot water use and about 10% compared to field test data (33).

3.4 Condensing Water Heater Model

Condensing water heaters are similar to traditional gas storage water heaters but feature a heat exchanger that allows the burner's combustion products to condense. This process provides additional heat to the water that would otherwise be vented outside. To model a condensing water heater, the conversion efficiency (essentially the combustion efficiency) of the water heater needs to vary with the temperature of the water next to the condensing heat exchanger and the part load ratio of the water heater if it modulates. The model developed here captures these effects. However, data on the exact efficiency of a condensing water heater as a function of tank temperature and part load ratio are limited. This model is based on a manufacturer's performance map (see Figure 12) and test results available in the literature (11). Detailed testing designed to develop a performance map of these units is required to create a fully validated model.

The condensing water heater model used here is based on the standard storage water heater model used for gas and electric water heaters previously described. However, a new model was used along with the storage tank model to capture the impacts of tank temperature and part load on overall efficiency. This new model is based on an existing model (38), which was designed to function as an external heating device for a water heater. The existing model would calculate how much energy was used and how much of that energy went into the tank for a gas or electric storage water heater with a constant efficiency. The new model uses a user-provided performance map to determine the efficiency of the unit based on a tank temperature from the storage tank model and a part load ratio from a temperature controller or a user-specified equation. This allows the model to be used with any potential control strategy a manufacturer may implement that can be modeled in the TRNSYS environment. This model is external to the tank model, so it can be used for tankless and tank condensing water heaters if sufficient data are available to develop a performance map. The impact of part load ratio can also be removed from the performance map if required (for example, for a unit that does not modulate).

The model developed here is based on one model of condensing water heater. This unit was chosen because the manufacturer published a performance map for it;d some test data on this unit are available in the literature (11). The performance map used by TRNSYS, created from this manufacturer's performance map, is shown in Figure 12.

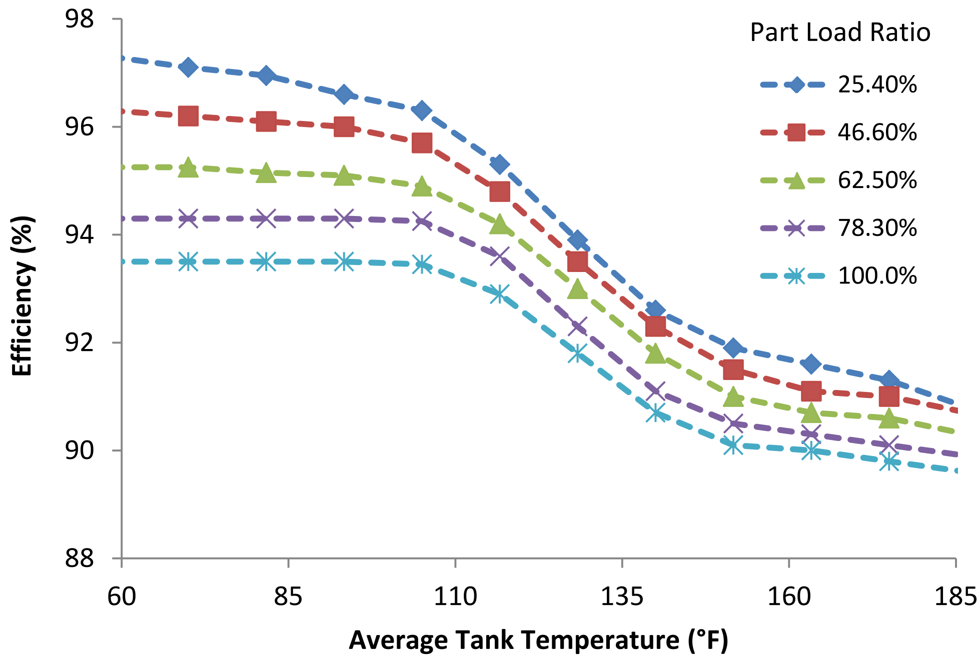

Figure 12. TRNSYS performance map for condensing water heater

3.5 Solar Water Heater Models

The solar water heater model used here consists of several connected TRNSYS components. The system comprises a storage tank, a flat plate collector, a pump, a controller, and pipes connecting the flat plate collector to the storage tank. Two types of solar water heating systems are considered. For an electric backup fuel source, a single storage tank with an electric resistance element near the top of the tank is used. For a gas backup fuel source, a two-tank system consisting of a solar storage tank with a separate gas storage water heater installed in line after the storage tank is used. The same gas water heater model that was used for the base case of a typical gas water heater is used as the second tank for this system. These systems were chosen as they are the most common type of solar water heating systems in the United States for each backup fuel source. Schematics of the solar water heater systems used here are shown in Figure 13 and Figure 14.

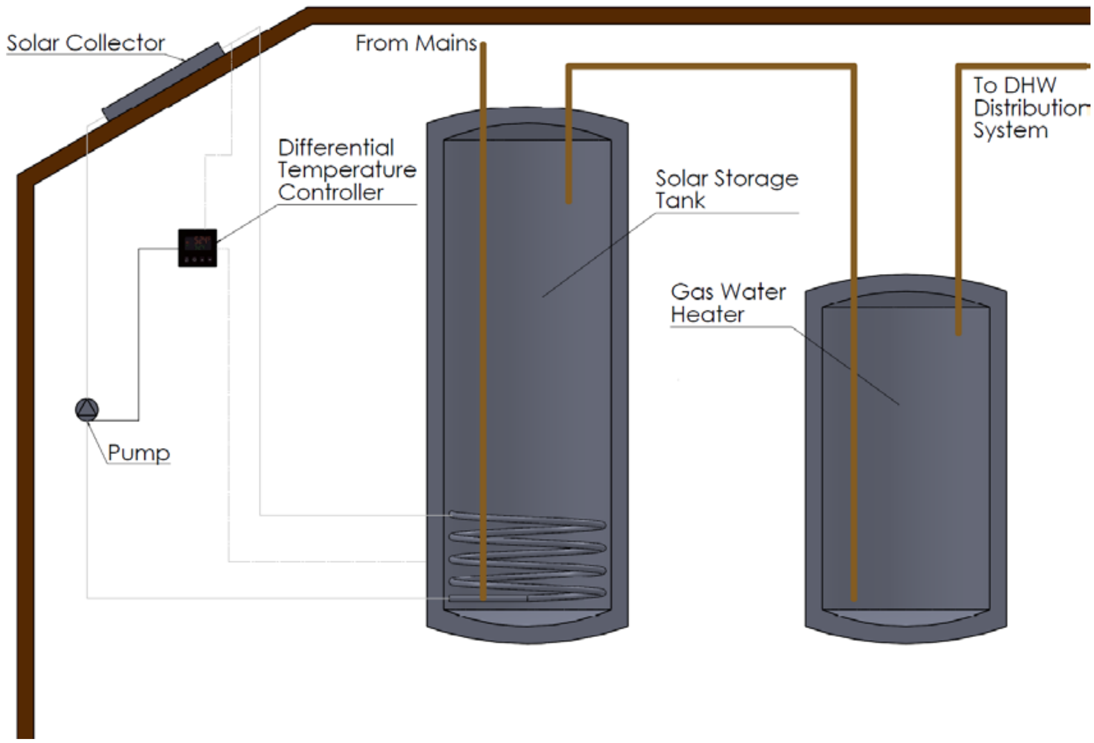

Figure 13. Schematic of solar water heater system with gas backup

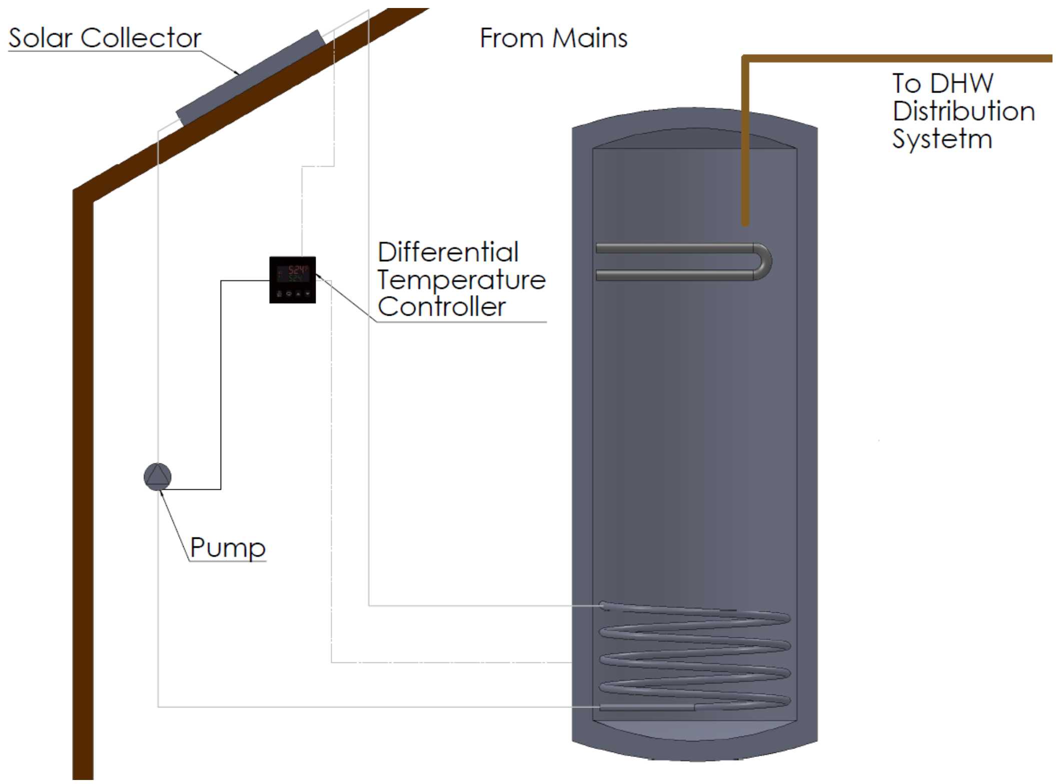

Figure 14. Schematic of solar water heater system with electric backup

The solar storage tank uses the same model as the electric and gas tank water heaters (30), but for a solar water heater a heat exchanger is also modeled. For a gas water heater, it is modeled as an immersed helical heat exchanger in the bottom of the tank. For an electric water heater, it is modeled as a wraparound heat exchanger wrapped around the bottom half of the tank. The storage tank used here is an 80-gallon model, sized based on a rule of thumb for solar water heaters to provide 20 gallons per occupant, which would correspond to a three-bedroom home (39). The actual tank volume of the storage tank is assumed to be 10% less than the nominal volume to be consistent with tank sizing regulations for electric water heaters. As previously discussed, the actual volume of a gas or electric water heater has to be only within 5% or 10%, respectively, of the rated volume, and most manufacturers make tanks with an actual volume at the lower limit of the allowed range. Because most manufacturers offer tanks with a backup electric resistance element for use in a single-tank system, the actual size is assumed be consistent with electric water heater sizing as opposed to gas water heater sizing. All flow is assumed to come directly into the bottom and leave from the top of the tank. The tank overall heat loss coefficient is taken from field testing of a solar water heater (40), which determined the overall heat transfer coefficient of a solar storage tank during use. The R-value from that particular tank is applied to this water heater to get a comparable overall heat transfer coefficient and takes into account differences in storage volume (and therefore surface area) between the two. The controller modeled here has a constant power consumption of 2 W.

For all solar water heaters, 50 feet of copper piping is assumed to connect the solar water heater to the storage tank, split evenly between the supply and return piping. Each is assumed to have ¾-in. thick pipe insulation with an R-value of 3.97 $ft^2 \cdot h \cdot °F/Btu \cdot in.$ along its entire length, which is the minimum insulation required for certification (41). The pipe specifications used here are consistent with SRCC guidelines for solar water heating systems (41). The first 20 feet of pipe entering and leaving the storage tank are generally assumed to be in the same location as the water heater; the remaining 5 feet are assumed to be outside. In the case of a solar water heater in a basement, the first 20 feet are assumed to be in conditioned space, as the pipes still have to reach the roof. Thus, most of their length will be in conditioned space. This allows the first 20 feet to interact with the space where the water heater is located, as all heat loss from this section goes into the space, influencing the heating and cooling loads. For all locations, two 32-ft^2 collectors connected in series were used, giving a net collector area of 64 ft^2.

3.6 Building Model

Climate can play an important role in determining the energy consumption and efficiency of water heaters. Water heater energy consumption and delivered energy vary with the incoming mains water temperature, which changes with location. In addition, the impacts of the water heater on space conditioning equipment energy consumption (primarily for water heaters in conditioned spaces) and the tank losses (primarily for water heaters in unconditioned spaces) vary with location. To capture the impacts of these factors, water heaters were modeled in several locations in a variety of U.S. climates.

The building model geometry was based on a TRNSYS model of a typical U.S. home (42); the remaining characteristics were based on the 2010 Building America Benchmark (12). These characteristics are representative of 2010 construction and are similar to those in the 2009 version of the International Energy Conservation Code (43). Although many building parameters were taken directly from the Building America Benchmark, there were several deviations. A complete description of the building, a list of deviations from the Benchmark, and a comparison of the buildings used here to benchmark buildings as modeled in the EnergyPlus version of BEopt (a software tool developed by the National Renewable Energy Laboratory) are provided in (33).

Seven of the eight Building America climate zones (44) are shown in Figure 15 (the eighth, subarctic, occurs only in Alaska and is not shown). The majority of the U.S. population lives in five zones: Marine, Hot-Humid, Mixed-Humid, Hot-Dry, and Cold. In general, one city was chosen as representative of each major Building America climate zone. However, two locations (Seattle, Washington and Los Angeles, California) were chosen in the marine zone to capture warm and cold marine climates. A list of the representative cities chosen for each climate zone is provided in Table 3 and a map of each city's location is shown in Figure 15. For each location chosen, a "typical" building (one that is largely consistent with the Building America House Simulation Protocol) was modeled.

Table 3. Representative Cities Used in This Study

Climate Zone	Representative City
Cold	Chicago, Illinois
Mixed-Humid	Atlanta, Georgia
Hot-Humid	Houston, Texas
Hot-Dry	Phoenix, Arizona
Marine (Warm)	Los Angeles, California
Marine (Cold)	Seattle, Washington

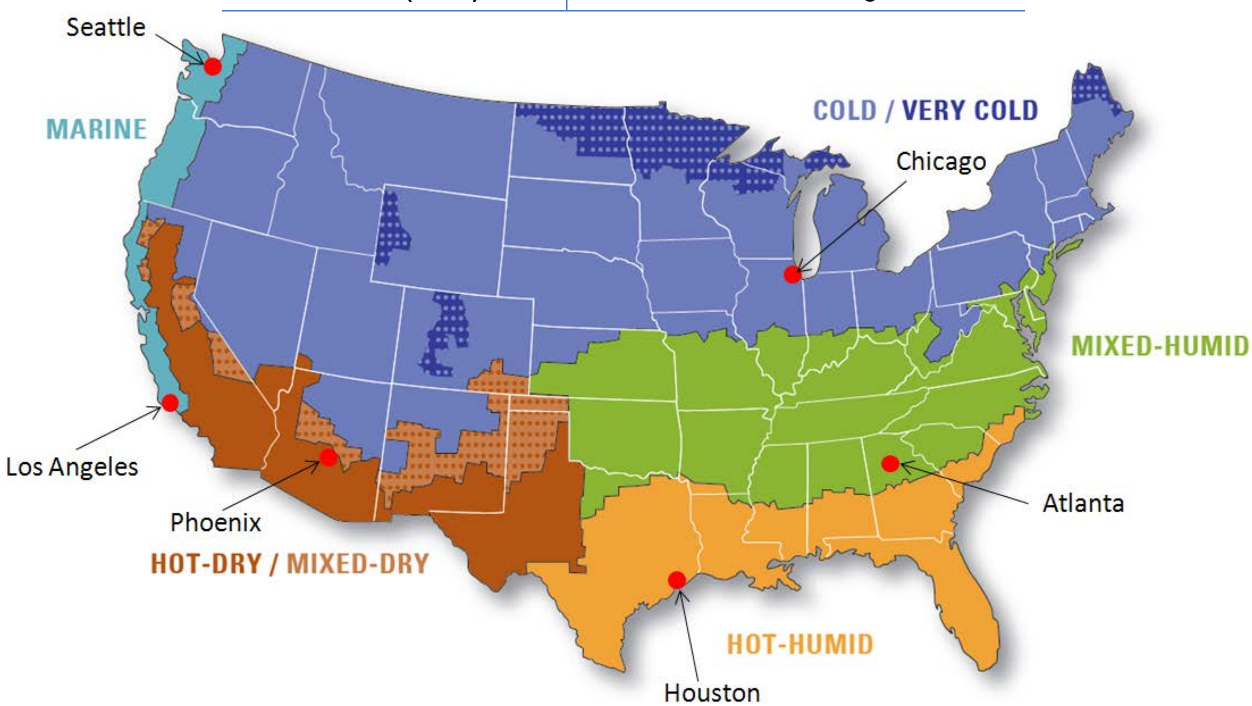

Figure 15. Building America climate zones (44) and the representative cities chosen for this study

In each location, a 2500-ft^2, two-story home facing due south with no neighbors was modeled. Its footprint is 42 ft × 30 ft. This home was assumed to have three bedrooms and two bathrooms and a 420 ft^2 (20 ft × 21 ft) garage attached to the south side (see Figure 16). Each also has a 6:12 pitched roof and an unfinished attic. For all locations, the heating set point was set to 71°F and the cooling set point was 76°F. No heating and cooling seasons (months where only the heating equipment or cooling equipment was on) were accounted for, and no setback was included.

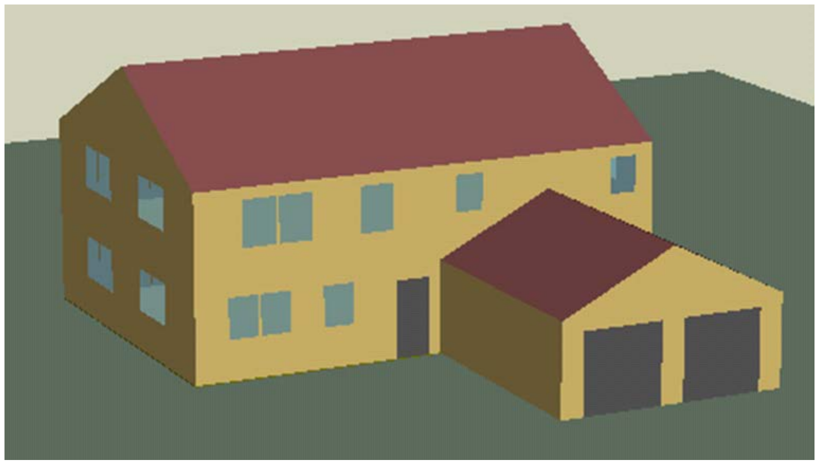

Figure 16. Geometry of the homes used in this study

The building envelope construction and U-values used here are based on the 2009 version of the International Energy Conservation Code (44), which prescribes R-values for the ceiling, walls, floor, and foundation depending on climate. Garage walls and ceilings used the same R-values as those used for the conditioned space. Each garage floor consisted of an uninsulated slab. In addition to the prescribed R-values, a framing factor was also applied to each home: 23%, 13%, and 11% for walls, floors, and ceilings respectively. Windows were also included and 18% of the total wall area was assumed to be windows. The building foundation type used here was determined based on whatever foundation was most common in that state (45). Basements were used in Chicago, Atlanta, and Seattle; a slab-on-grade foundation was assumed for Los Angeles, Phoenix, and Houston. Foundations were modeled using the DOE2 Winklemann methodology (46).

Two types of space conditioning equipment are considered here: a furnace and an air conditioner (AC) for homes with gas water heaters and an air source heat pump (ASHP) for homes with electric water heaters. These two types of equipment were considered, because a home that has gas service is likely to use it for both water heating and space heating; one without is assumed to use electricity for both. This assumption was made as mixed fuel cases (where electricity is used for space heating and gas is used for water heating or vice versa) are less common. The space conditioning equipment assumed here is consistent with the Building America Benchmark. In all homes, no dehumidification equipment was installed and ducts were not modeled.

For homes that have gas service, the AC and the furnace need to be correctly sized. All equipment was sized using design day simulations in BEopt 1.1; the furnace, AC, and air handler size used in each house are provided in Table 4. The furnace was modeled as having a constant efficiency equal to the rated Annual Fuel Utilization Efficiency (AFUE) of a Building America Benchmark furnace: 78%. For all homes, a seasonal energy efficiency ratio (SEER) 13 AC unit was modeled. Performance maps for the AC were taken from past work (42) that created TRNSYS specific performance maps for a SEER 13 unit.

Table 4. Furnace, AC, and Air Handler Sizes

Location	Furnace Size (kBtu/h)	AC Size (tons)	Air Handler Flow Rate (cfm)
Atlanta	40	3	1000
Chicago	50	3	1000
Houston	40	3	1000
Los Angeles	30	2	600
Phoenix	30	4	1400
Seattle	30	2	600

An air handler is required to move air from the space to the conditioning equipment. Each air handler was sized based on the AC size provided by BEopt with the flow rate proportional to the AC size. The fan power in the air handler is 0.59 W/cfm. The fan motor was modeled as being 90% efficient, and any losses from the motor were assumed to become heat added to the airflow through the fan.

All homes with an ASHP used a 7.7 HSPF/SEER 13 unit. For heating, the ASHP had two-stage backup electric resistance heaters that turned on if the outside air temperature was too low for the ASHP to operate. The first resistance heater, with a capacity of 5 kW, turns on if the outdoor air temperature drops below 40°F. The second heater, with a capacity of 10 kW, turns on if the outdoor air temperature drops below 25°F. A crankcase heater with a power draw of 0.02 kW is used to keep the unit operating effectively if the outside air temperature drops below 50°F and heat is required. The ASHP uses the same air handler as was used in the furnace and AC case for a home in the same location.

3.7 Domestic Hot Water Use

As water heater energy consumption was the focus of this work, a detailed DHW schedule was used. Many water heaters, including tankless and HPWHs, need a subhourly draw profile with discrete events to accurately model their performance. For this analysis, a 6-second time step was used for the draw profiles. The Building America Domestic Hot Water Event Schedule Generator (DHWESG) was used to provide the necessary discrete draw profile (34). The DHWESG is a statistical tool that generates discrete events based on a probability distribution of draw events corresponding to the average distribution of hourly hot water use included in the Building America House Simulation Protocols (12). The DHWESG is based on studies of residential hot water use and uses separate probability distributions for each end use (showers, baths, clothes washing, dishwashing, and sinks) (47). For each day, a number of discrete events for each end use are assigned based on distribution functions for each fixture. The event schedule generator assigns these events to different times of day in a way that takes into account the results of the studies, including event clustering for events of the same end use, differences in weekday and weekend hot water use and several vacation periods per year. Vacations occur for three days in May, one week during August, and four days in December. A sample day of draws with all end uses aggregated is compared to the House Simulation Protocols draw event probability in Figure 17.

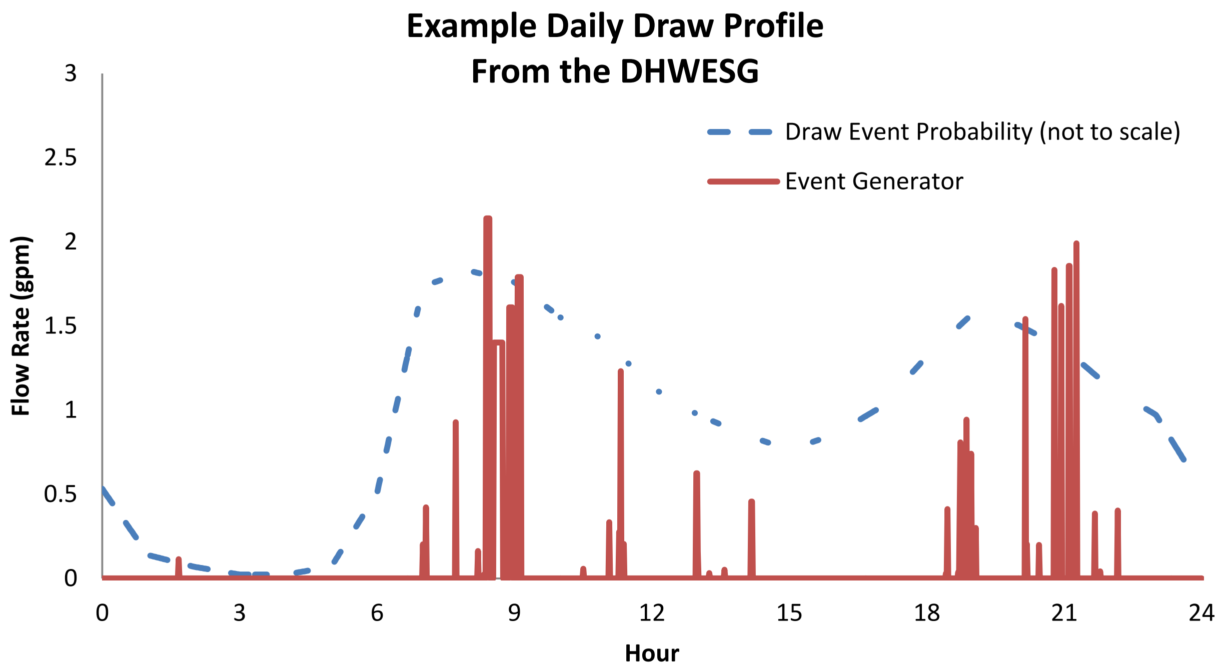

Figure 17. Example daily draw profile

The DHWESG creates a full year of unique draw events similar to those shown in Figure 17. Events have a specified mixed flow rate, which is what an occupant would actually use for sink, shower, and bath draws. For these events, a homeowner will temper the hot water with cold mains water to a useful temperature. The mains water temperature used here is calculated based on an algorithm developed at the National Renewable Energy Laboratory (48). Annual mains water temperature profiles for all sites are provided in Figure 18. For this work, the useful temperature is defined as 105°F and all water heaters have a set point temperature of 120°F. Specifying a mixed flow rate as opposed to a hot flow rate allows the amount of hot water drawn to vary with mains water temperature, which leads to different volumes of water being drawn at different locations and times of the year. For appliance draws (clothes washer and dishwasher), the hot flow rate is specified, because these devices generally do not temper the incoming hot water to any specific temperature. A time step must also be specified to use the DHWESG. Some of the models used here require very small time steps to capture the dynamic of the water heater (for example, the heating and cooling of the heat exchanger in a tankless water heater). A 6-second time step was used to ensure these dynamics were fully captured.

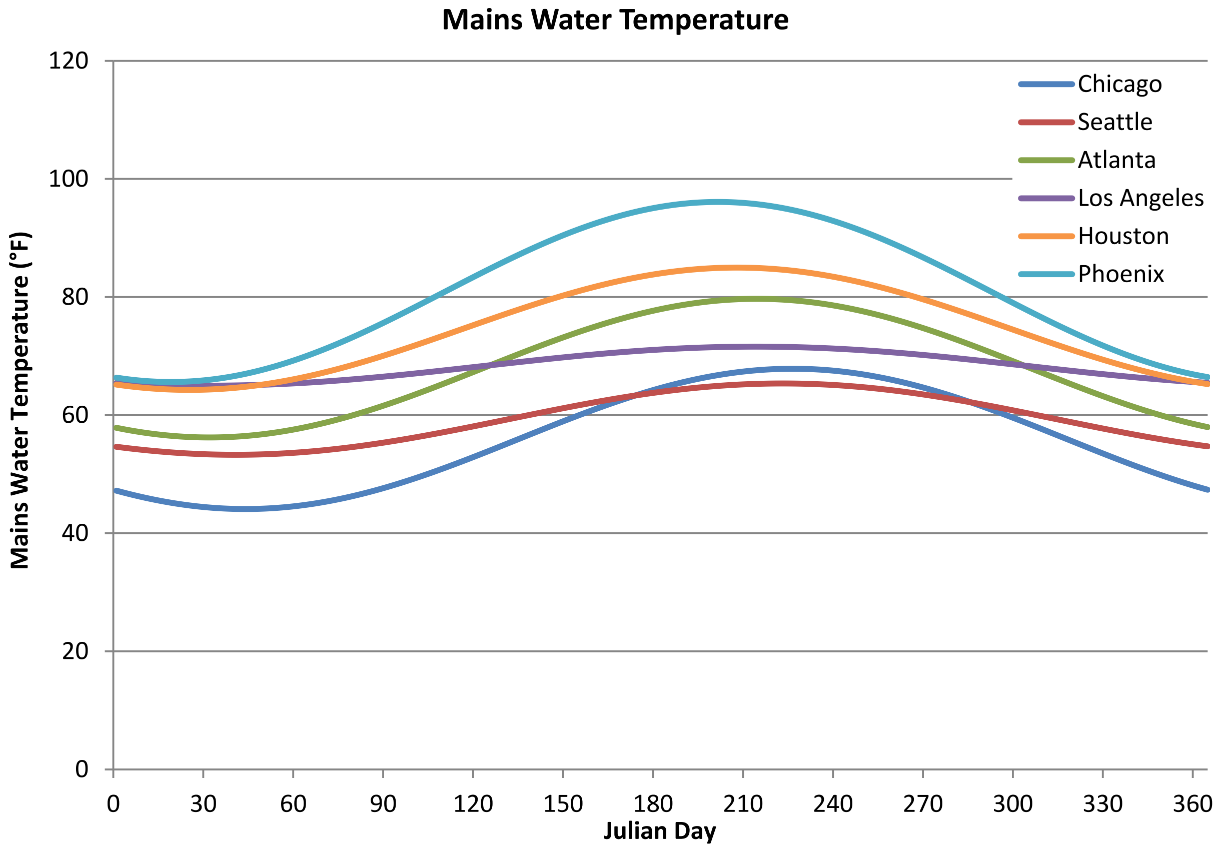

Figure 18. Annual mains water temperature for all locations

The amount of DHW used by a household is highly variable. Although the volume of water drawn can be roughly tied to the number of occupants (and as a result, the number of bedrooms), a substantial variation can occur depending on occupant behavior. To try to capture this behavior, three draw profiles were created and used in this work. These correspond to one-, three-, and five-bedroom homes in the DHWESG and are intended to represent low, medium, and high DHW users. The profiles are based on assuming a different number of bedrooms in a home, but all are used in a home of the same size to capture behavior variations, which can lead to large differences in hot water use between two homes with the same number of occupants.

The full annual draw profiles are too large to be included here, although summary statistics are provided. Figure 19 provides the annual draw volume broken down by end use for medium-use homes. Figure 21 provides the volume of mixed water drawn each month for all three draw profiles. Although the events generally average out to the hourly profile shown in Figure 17, day to day (and even month to month) the volume of water drawn will not perfectly average out to this draw profile. Widely different daily and monthly draw volumes may be specified in the DHWESG. As a result, the draw volumes in Figure 21 do not linearly scale as the use increases from low to high. Cumulative frequency distributions of event draw volumes, duration, flow rate, and time between draws are given in Figure 21, Figure 22, Figure 23 and Figure 24 respectively.

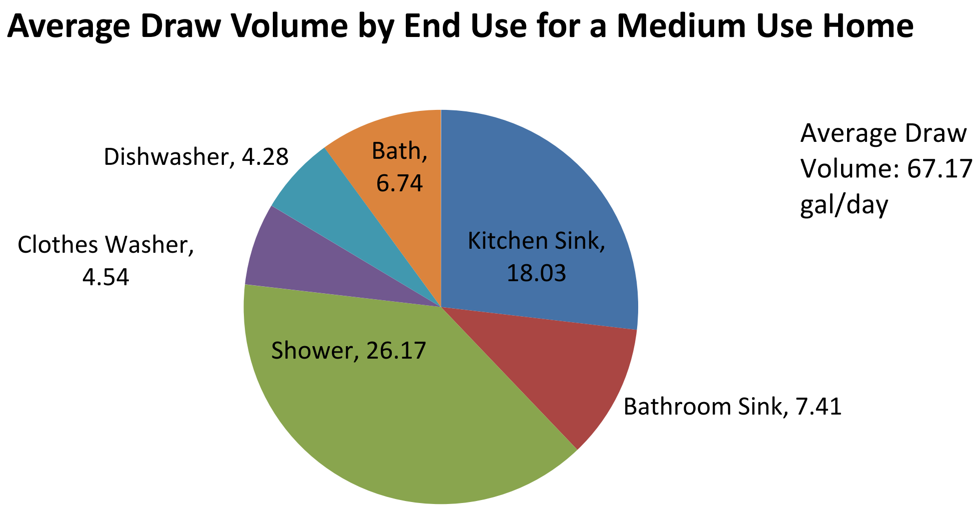

Figure 19. Annual average draw volumes by end use for a medium-use home. For clothes washers and dishwashers the volume of hot water drawn is shown; for all other draws the mixed volume is shown.

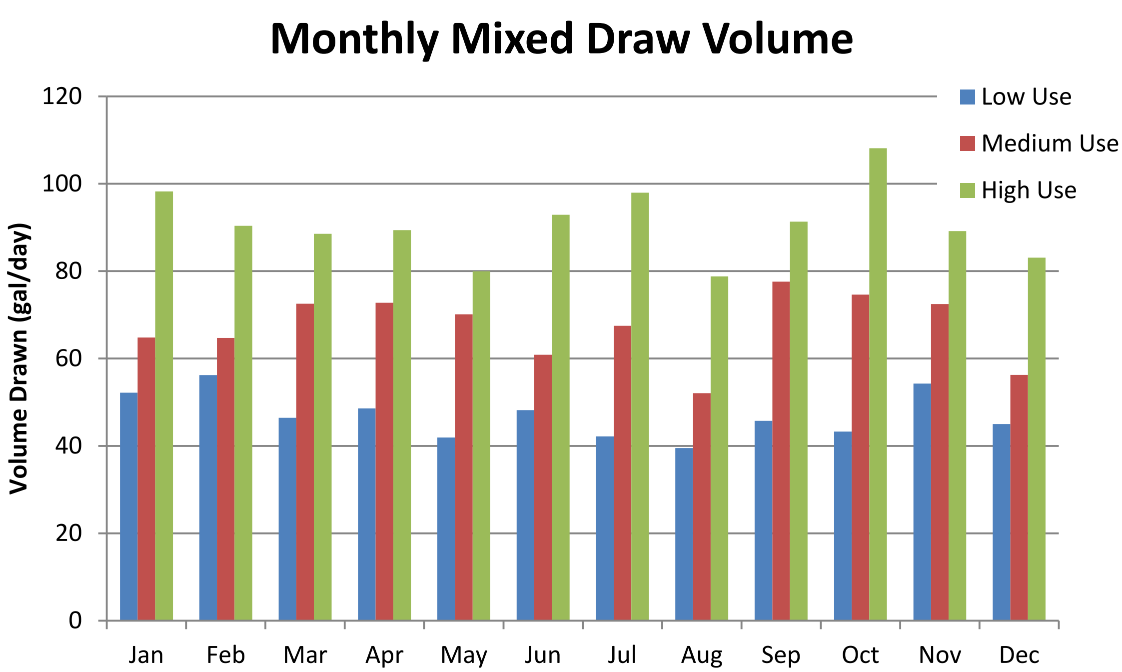

Figure 20. Monthly mixed draw volumes

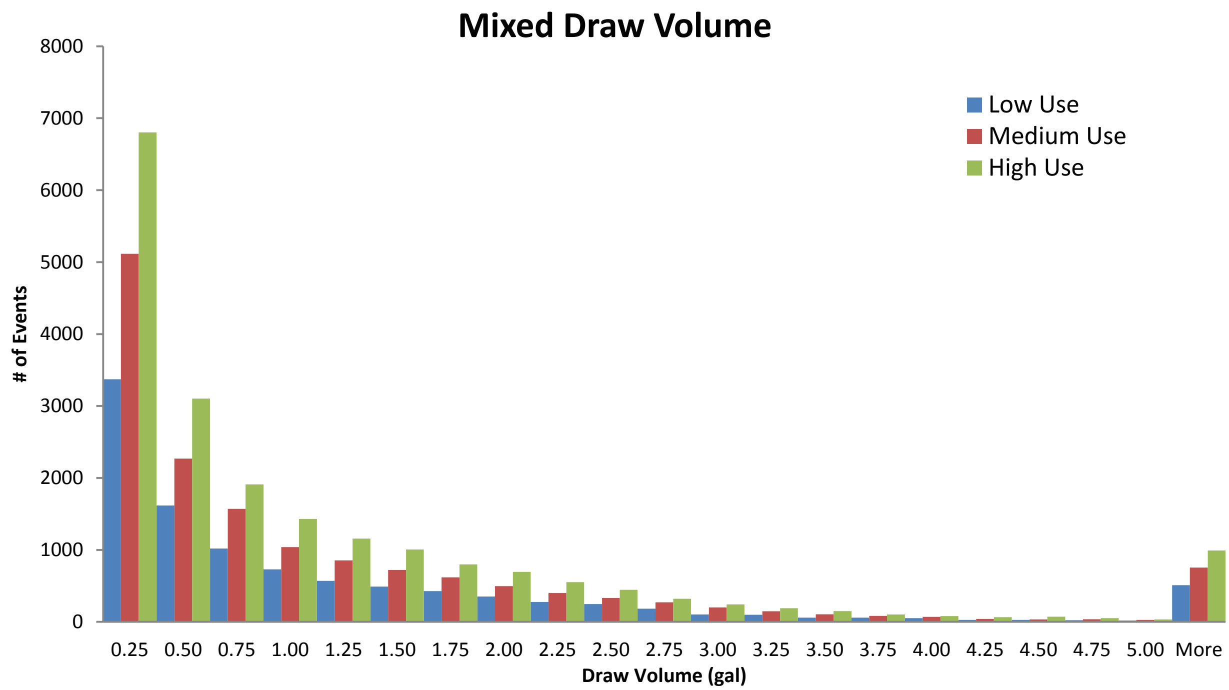

Figure 21. Histogram of mixed draw volume

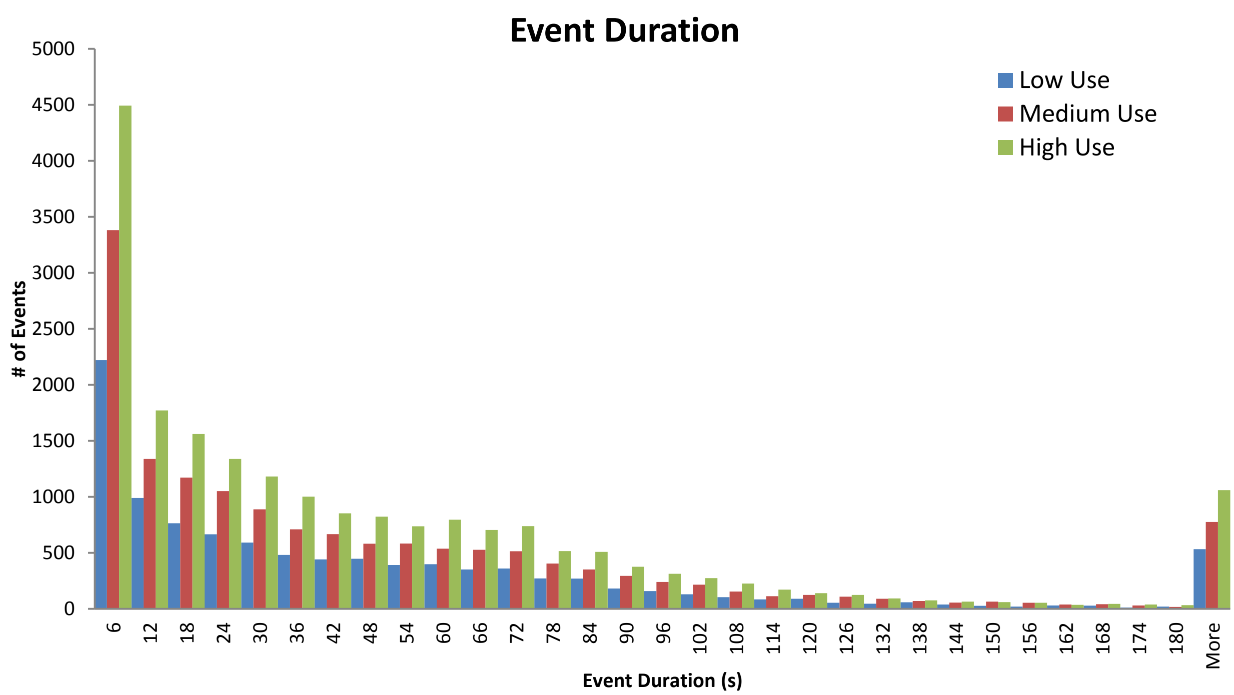

Figure 22. Histogram of event duration

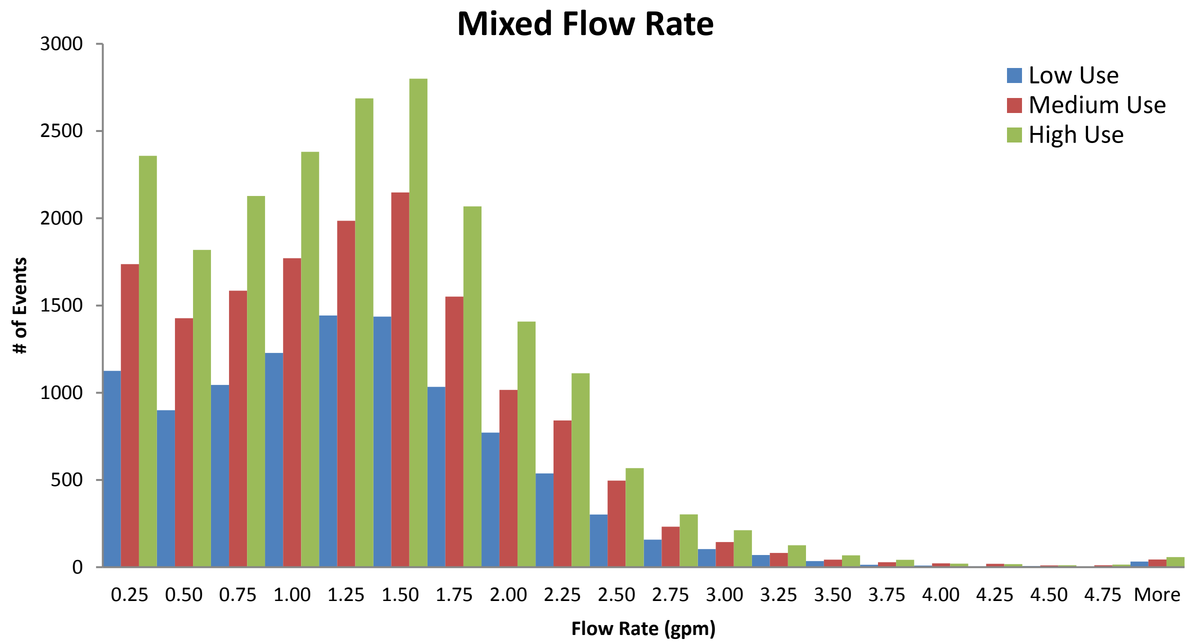

Figure 23. Histogram of mixed flow rate

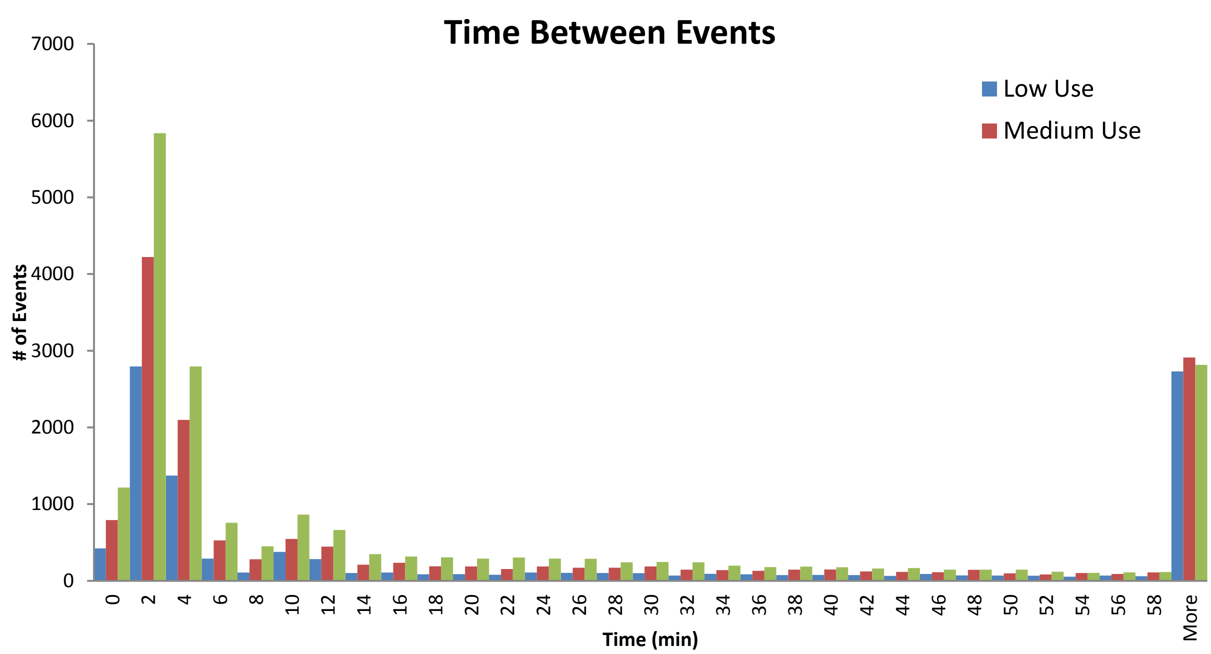

Figure 24. Histogram of time between events

Mixed draw volumes are provided here as the mixed volume does not vary with location. The actual hot draw volume for each location will depend on both the climate and the water heater modeled. Some water heaters may allow the outlet temperature to significantly sag below the set point temperature, which will increase the volume drawn from the tank during mixed draw events. The hot water draw volume used in each case is provided in Appendix C.

4 Energy Analysis

Annual simulations were performed to answer several key questions about the performance of the water heaters modeled here. For the six representative cities (Chicago, Illinois; Seattle, Washington; Atlanta, Georgia; Los Angeles, California; Houston, Texas; and Phoenix, Arizona), a parametric analysis was performed of all types of water heaters considered here. They were simulated being subjected to low, medium, and high draw profiles in conditioned or unconditioned spaces. Annual simulations were used to determine the most energy-efficient option and the most cost-effective option in each case. Equipment degradation was not considered.

When comparing water heaters in the same location, several factors besides energy consumption need to be considered. To keep the comparison as even as possible, all water heaters should meet the same load. Some technologies, such as HPWHs and tankless water heaters, may have trouble meeting the load, because outlet temperatures sag or because of delays between water being drawn and the burner firing, respectively. Solar water heaters may provide water at a higher temperature than required because of the higher temperatures allowed in the storage tank, which will reduce the volume of hot water drawn during mixed draws. To ensure that all water heaters met the load, their energy use was normalized to account for unmet load. In actual use there would be no normalization energy, although homeowners may change their hot water use or change the set point temperature of their water heaters if they frequently experience unacceptable sag in the outlet temperature. However, including normalization energy ensures that water heaters that frequently have sag in the outlet temperature do not get an efficiency benefit from this sag. The normalization energy is defined as the additional thermal energy required to meet the load divided by the instantaneous efficiency of the water heater (see Equation 1).

$$E_{nrmlz} = \frac{mc_p(T_{out} - T_{req})}{\eta} \quad (1)$$

where,

E_{nrmlz}	=	the normalization energy consumption,
m	=	the mass of water drawn during the time step,
T_{out}	=	the water heater outlet temperature,
T_{req}	=	the required outlet temperature to meet the load, and
η	=	the instantaneous efficiency.

The instantaneous efficiency is defined (Equation 2) as:

$$\eta = \frac{E_{del}}{E_{cons}} \quad (2)$$

where,

E_{del} = the delivered energy and

E_{cons} = the consumed energy.

If at any time step the outlet temperature was lower than required to meet the load (105°F for mixed draws and 120°F for hot draws), the normalization energy was calculated. All the water heaters required some normalization energy, but the amount varied by technology.

Different water heaters had different losses to their surroundings, which impacted the space heating and cooling loads. Changes in heating, cooling, and fan energy consumption were considered in all comparisons between technologies. The overall energy consumption can therefore be calculated by Equation 3:

$$E_{WH,net} = E_{WH} + E_{nrmlz} + \Delta E_{heat} + \Delta E_{cool} + \Delta E_{fan} \quad (3)$$

where,

$E_{WH,net}$ = the overall energy consumption,

E_{WH} = the water heater energy consumption,

E_{nrmlz} = the normalization energy consumption,

ΔE_{heat} = the change in space heating energy consumption,

ΔE_{cool} = the change in space cooling energy consumption, and

ΔE_{fan} = the change in air handler fan energy consumption.

For each comparison, the changes in space heating, cooling, and fan energy consumption were calculated relative to the base case (gas storage for gas water heaters and electric storage for electric water heaters). This provided the overall net energy consumption of one water heater relative to another. For electric water heaters, an ASHP was used for both heating and cooling. For gas water heaters, a furnace provided heating and an AC provided cooling. This is based on the assumption that a home with natural gas available will use it for both space heating and water heating. Therefore, electric and gas water heater energy consumption cannot be directly compared because the change in space heating and cooling energy consumption is different in these cases, and switches in water heating fuel sources (say from a gas storage to a HPWH) are not considered here.

Gas and electricity consumption needs to be considered for gas water heaters. Tankless, condensing storage, and solar water heaters all consume some electricity via controllers, venting fans, freeze protection, or pumps, depending on the technology. In addition, the cooling and air handler energy consumption differences are electric; the water heater, normalization, and heating energy consumption are gas. All comparisons are done on a source energy basis so water heaters that use both gas and electricity can be fairly compared. Source energy takes into account the energy used at the site as well as all energy required to extract, convert, and transmit the primary energy from an energy source. National average site-to-source multipliers of 3.365 and 1.092 are used for electricity and natural gas, respectively (12).

Unconditioned space is defined as a basement (if the home has one), or as a garage otherwise. Homes in Chicago, Seattle, and Atlanta have basements; those in Los Angeles, Houston, and Phoenix do not. Basements are much more closely linked to conditioned spaces and ground temperatures than garages and have smaller temperature swings. Additionally, the space heating and cooling impacts of water heaters installed in basements are greater than those of water heaters installed in garages.

In Sections 4.1–4.7, the water heater site energy consumption is examined independent of normalization energy and changes in heating, cooling, and fan energy consumption. This allows for analysis of how climate, draw profile, and water heater location affect energy use independent of second order effects such as the change in space conditioning energy consumption and normalization energy. Appendix D provides detailed site energy consumption of water heaters considered here as well as tank losses and delivered energy for all cases. In Sections 4.8 and 4.9, electric and gas water heaters are compared on a source energy basis to determine the optimal water heater type from an energy perspective in each case. In many cases the efficiency is highly dependent on the draw volume, so the volume of water drawn by the water heater for every scenario investigated here is given in Appendix C. Appendix C shows that not every water heater has the same hot water draw volume. These differences stem from differences in the operation of these units, which lead to variations in the outlet temperature. Lower outlet temperatures lead to additional hot water being drawn to provide water at the mixed setpoint temperature. If the outlet temperature falls below the mixed draw temperature, the shortfall is addressed via the previously described normalization energy. However, in actual homes there is no normalization energy and occupants may instead change their behavior such that the water heater is able to meet the load.

4.1 Electric Storage Water Heater

The largest factor impacting the efficiency of electric storage water heaters is the amount of water drawn. As the amount of water drawn increases, so does the amount of energy delivered and the ratio of useful energy (delivered hot water) to wasted energy (tank losses). This leads to the higher efficiency in climates such as Chicago with colder mains water temperatures compared to locations with warmer mains water temperatures such as Phoenix (see Figure 25). The energy consumption is also much greater in cases with colder mains temperature because more energy is required to bring the water up to a useful temperature. When these water heaters are installed in unconditioned spaces, the tank losses vary depending on the space temperature. This leads to lower tank losses in cooling-dominated climates such as Phoenix and higher losses in heating-dominated climates such as Chicago. This change impacts the efficiency, leading to the roughly uniform efficiency shown in Figure 26. It also increases energy consumption in cold climates and reduces it in warm climates.

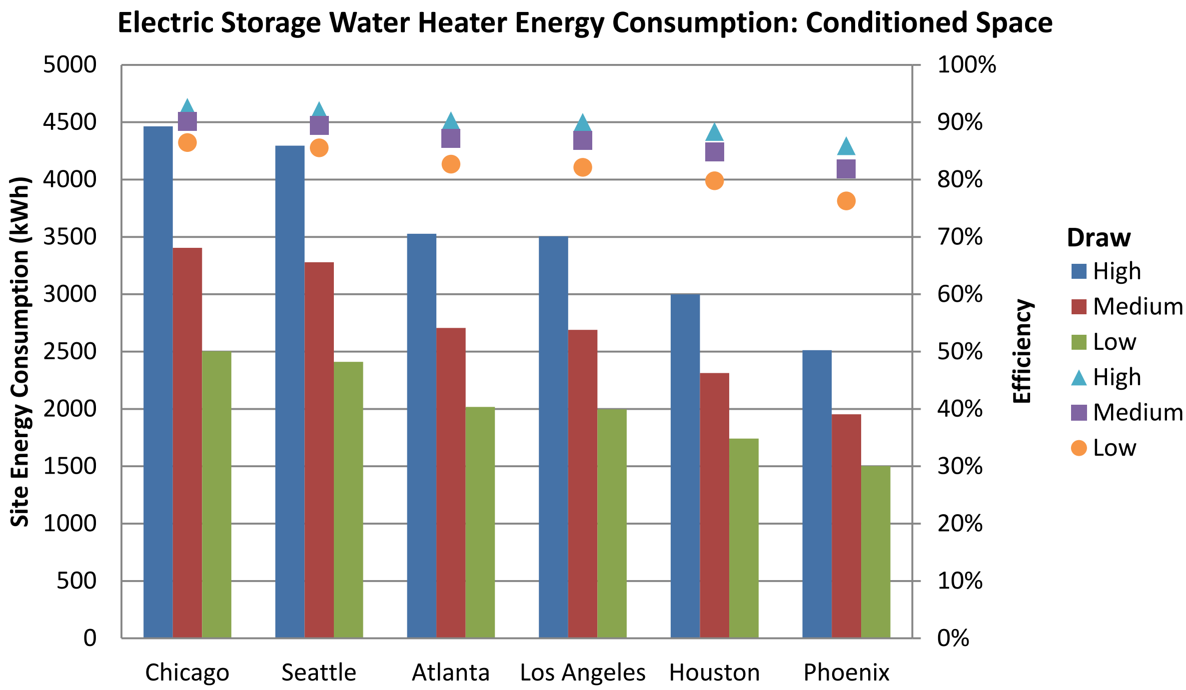

Figure 25. Electric water heaters in conditioned spaces—annual energy consumption

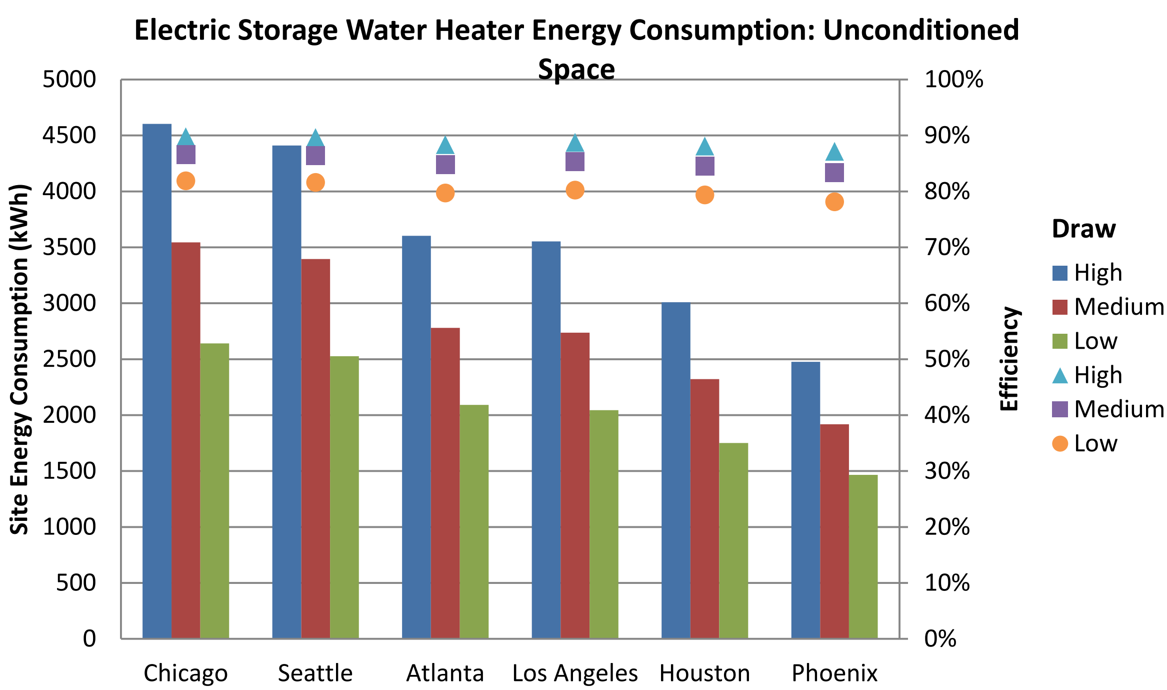

Figure 26. Electric water heaters in unconditioned spaces—annual energy consumption

4.2 Heat Pump Water Heater

Many factors affect HPWH efficiency, especially mains water temperature, the wet bulb temperature of the surrounding air, and the draw profile. For large draws, the heat pump will not have enough capacity to recover quickly, so the elements turn on. Thus, HPWHs are different from most other water heaters in that their efficiency does not always increase with draw volume. Figure 27 and Figure 28 show that the most efficient case for HPWHs is the medium draw profile (in the case of Phoenix, medium and high draw cases have roughly equivalent efficiency).

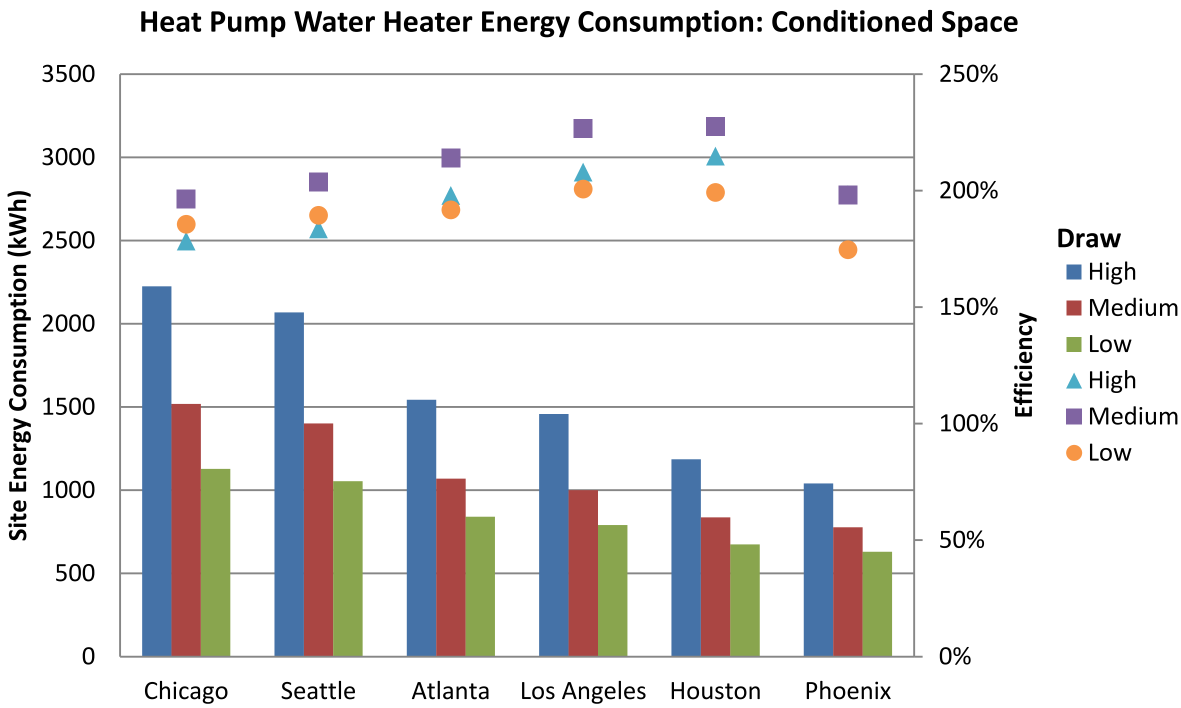

Figure 27. HPWHs in conditioned spaces—annual energy consumption

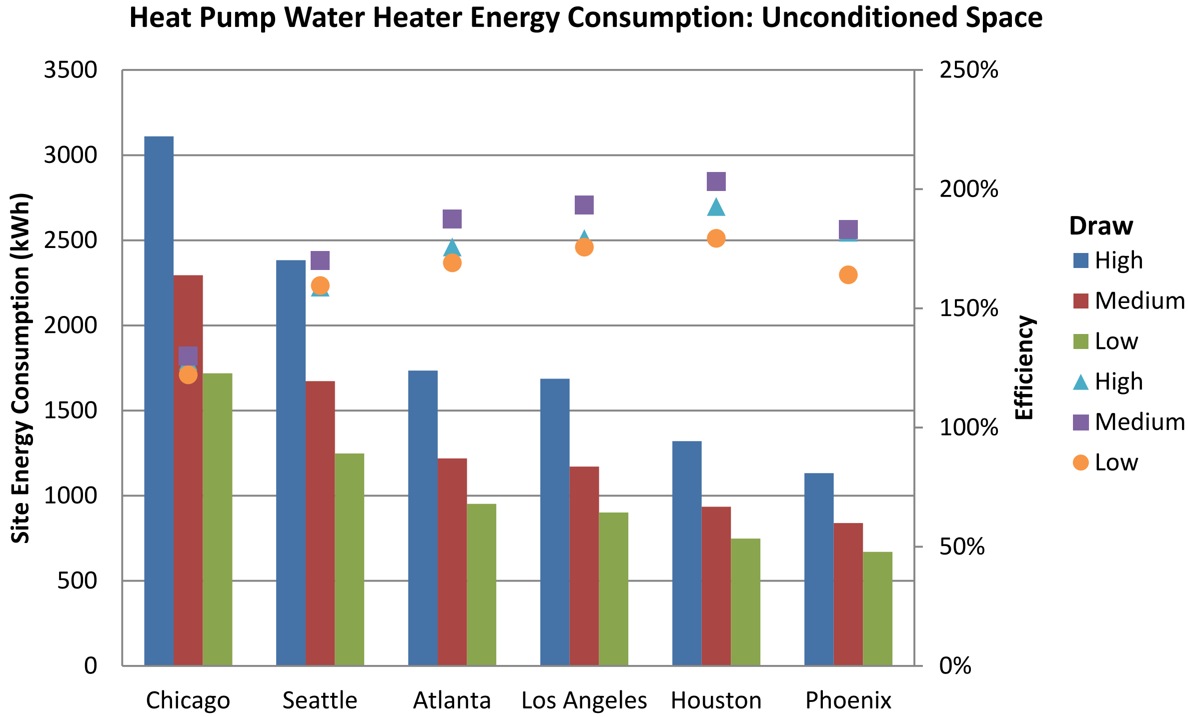

Figure 28. HPWHs in unconditioned spaces—annual energy consumption

Figure 29 through Figure 31 illustrate this phenomenon further. The daily HPWH system COP (defined as the energy delivered by the storage tank divided by the energy consumed by the heat pump, electric resistance element, fan, and controls) is shown for homes in Houston with the HPWHs in conditioned spaces for low, medium, and high draw profiles, respectively. There are generally two discrete clusters of system COP data points: the upper group is when the HPF (defined as the amount of heat added to the tank by the heat pump divided by the amount of heat added by both the heat pump and the elements) = 1; the lower group is when the HPF is < 1. For this HPWH with the modeling assumptions used in this study, once the electric elements come on, they stay on until the tank fully recovers, leading to very few cases where an HPF is just slightly less than 1. The HPF is much more likely to be < 1 for higher use homes, as the electric elements are triggered by the tank having had enough water drawn to require the faster recovery rate of the elements as opposed to the heat pump.

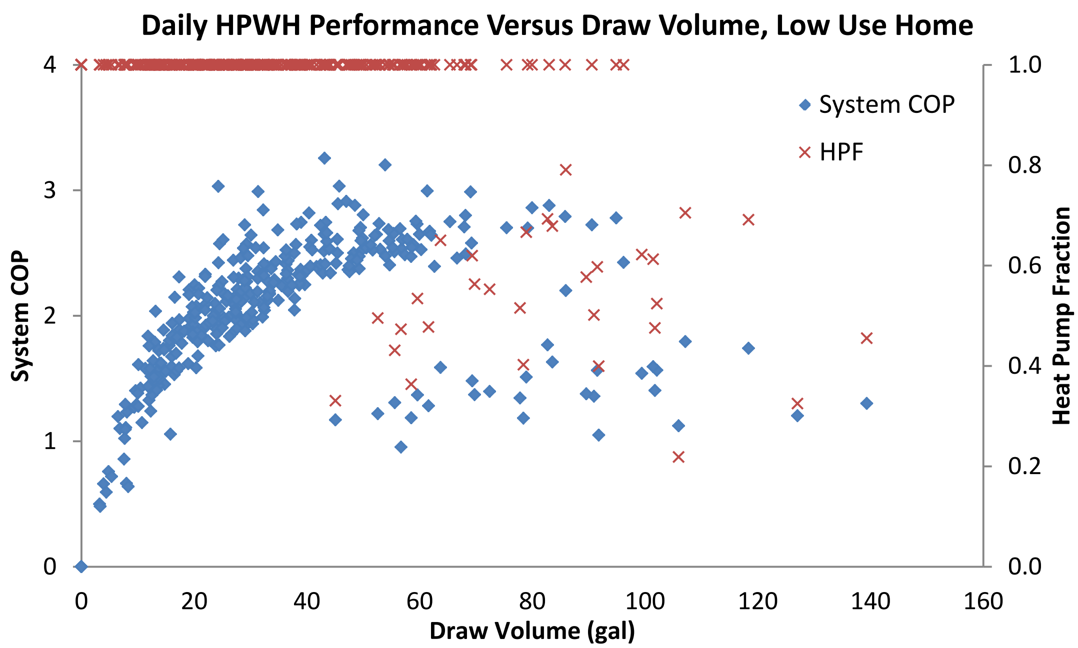

Figure 29. Daily HPWH efficiency for a low-use home in Houston

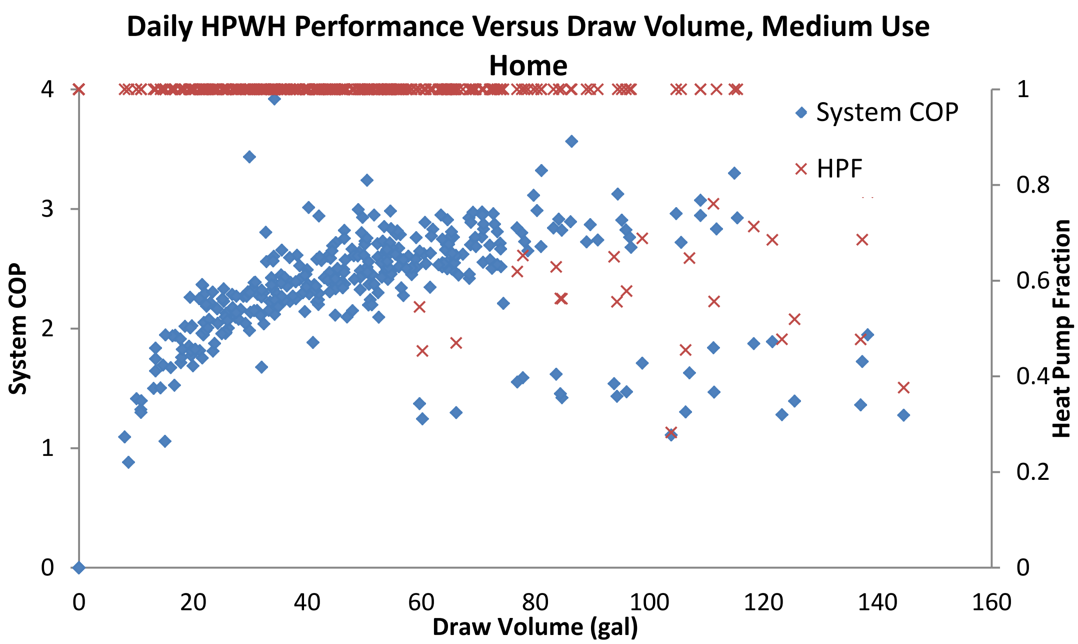

Figure 30. Daily HPWH efficiency for a medium-use home in Houston

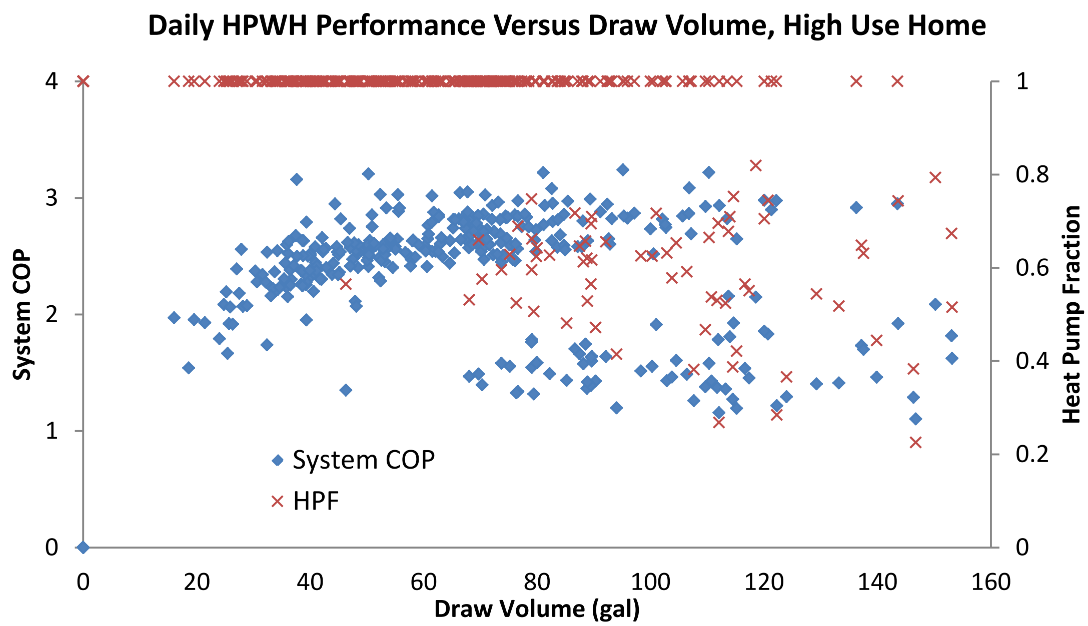

Figure 31. Daily HPWH efficiency for a high-use home in Houston

In the low-use case (Figure 29), relatively few days show an HPF < 1. However, the lower use also leads to lower efficiency, as the system COP of the HPWHs trends with the log of the daily draw volume. The medium-use case (Figure 30) has a few more points with an HPF < 1, but the higher draw volume leads to a higher average system COP that makes up for this difference. The high use case (Figure 31) shows significantly more days with an HPF < 1, leading to lower annual efficiency. Only the home in Houston with the HPWH in conditioned space is shown here, but this same trend is seen in all cases. Different HPWH control logic can greatly influence the HPF and other HPWHs will behave differently.

When a HPWH is in conditioned space, the ambient air temperature is kept at 71°–76°F; mains water temperature and humidity vary. This provides more consistent inlet air conditions, leading to the lower variability in efficiency between sites for the conditioned space case than for the unconditioned space case. However, changes in the space heating and cooling energy consumption are not taken into account in this section. These changes increase the energy consumption of space conditioning equipment in heating-dominated climates and lower it in cooling-dominated climates.

HPWH efficiency is increased by colder mains temperature; however, the inlet air wet bulb temperature is the main factor. Thus, Houston has the highest efficiency and Chicago has the lowest. HPWHs also have lower and upper limits on the ambient air temperature. Above or below these limits (45°–120°F for the unit modeled), the heat pump will not operate. Thus, during some times of the year, the system behaves identically to an electric water heater, especially in cold climates such as Chicago. The efficiency drop in Phoenix relative to Houston and Los Angeles can also be partially explained by the dry air lowering the wet bulb temperature relative to the other locations, which is the main factor influencing the heat pump performance. The higher mains temperature and resulting lower average draw volume also decrease the efficiency in Phoenix relative to these locations.

4.3 Solar Water Heater With Electric Backup

For solar water heaters, the main driver for efficiency (SEF) is the amount of solar radiation received. SEF is defined as the amount of energy delivered to the storage tank by the solar collector divided by the total energy input into the tank. SEF can be written (Equation 4) as:

$$SEF = \frac{E_{del}}{E_{cons}+E_{par}} \tag{4}$$

where,

E_{del} = the energy delivered by the water,

E_{cons} = the energy consumed by the water heater to heat the water, and

E_{par} = the parasitic energy consumption of the system.

The parasitic energy consumption takes into account any energy consumed by the pumps for this active solar system as well as a constant 2 W draw from the controller (49). Solar water heaters are different from gas and electric storage water heaters, where efficiency is largely driven by the amount of hot water drawn. Instead, the efficiency is largely driven by the amount of solar radiation at the site. Thus, the trends in efficiency and energy consumption differ from those for electric storage water heaters (see Figure 32 and Figure 33). A map of the solar radiation across the United States is provided in Figure 34 to help illustrate how solar radiation drives this trend. Latitude also has some impact. For solar water heaters, the optimal orientation for mounting the collector is approximately due south with a tilt roughly equal to the latitude. All solar water heaters considered here are mounted flush with the roofs, which have a 6:12 pitch (26.57 degrees) at all locations. The farther north the solar water heater is, the less optimal this installation angle is. However, solar water heater performance decreases only modestly with this angle, as the collector should still receive 90% of the insolation as if it were mounted at the optimal angle (50). For this study, only one size of solar water heater was used with an 80-gallon storage tank and 64 ft^2 of collector area. This is a typical system size that performs well in most climates. However, it is oversized for locations with a large solar resource, particularly Phoenix.

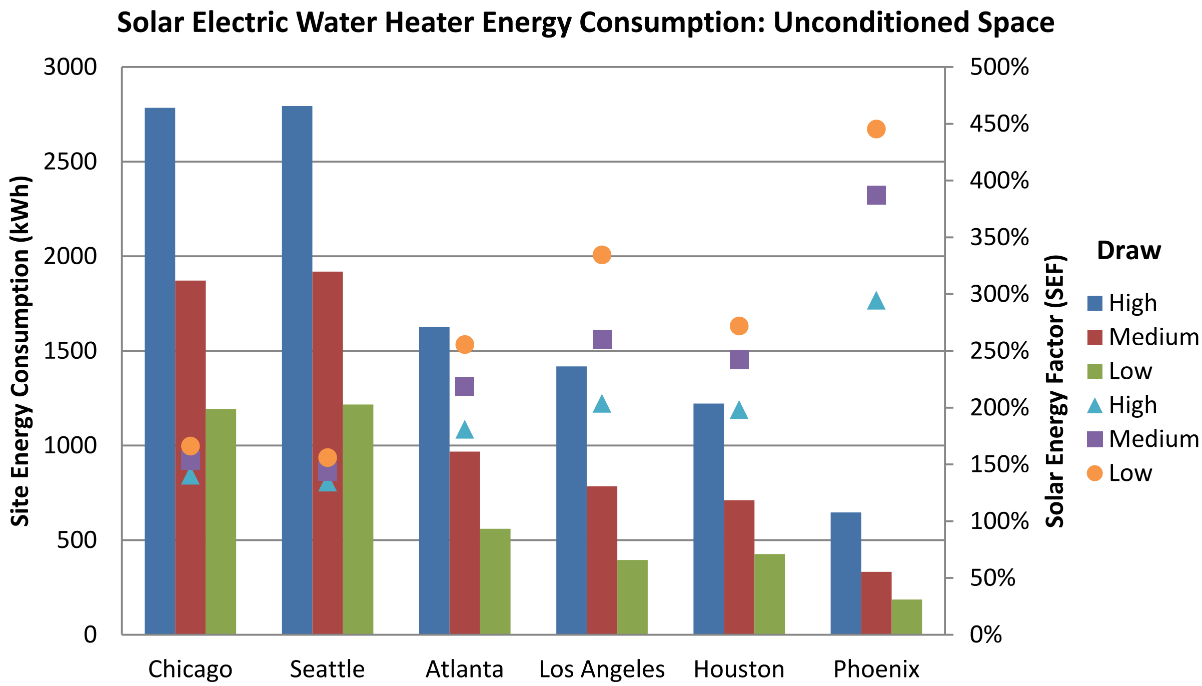

Figure 32. Solar water heaters with electric backup in conditioned spaces—annual energy consumption

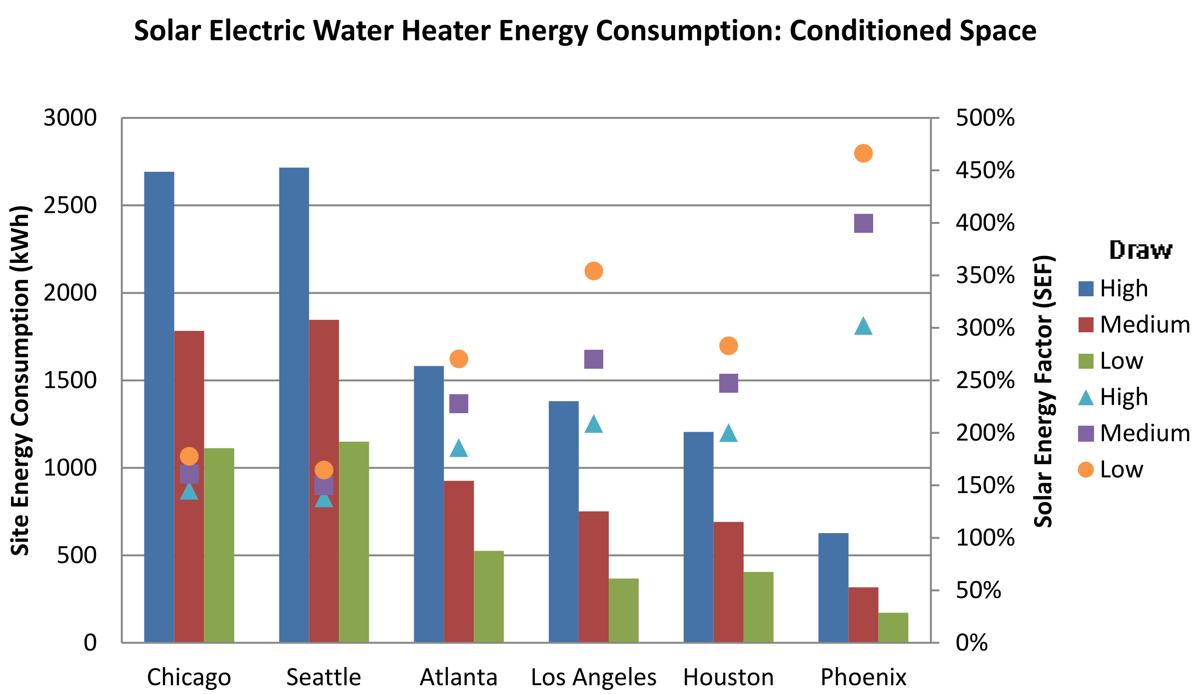

Figure 33. Solar water heaters with electric backup in unconditioned spaces—annual energy consumption

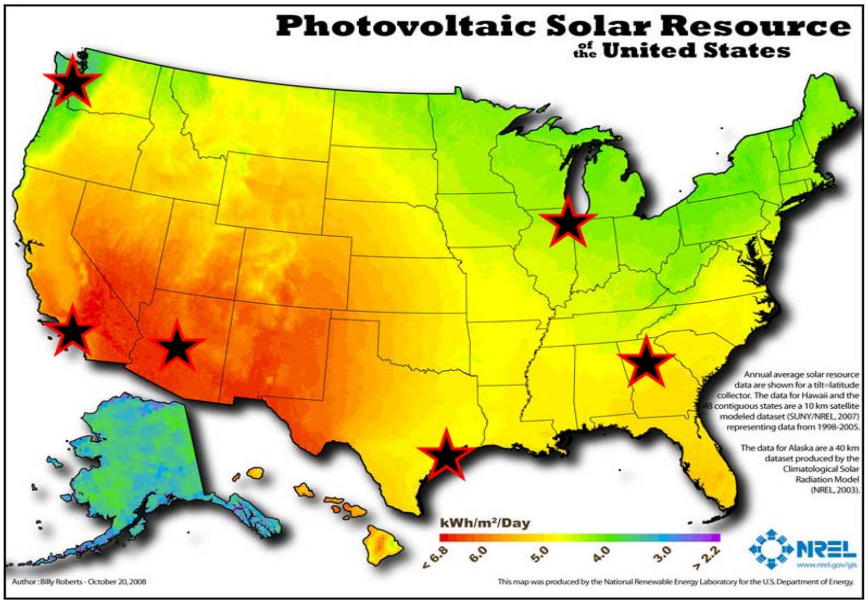

Figure 34 Average U.S. solar resource. Stars denote the representative cities used in this study.

(Image credit: Billy Roberts/NREL)

For all sites, the SEF decreases with increasing draw volume, because the solar collector can supply a roughly set amount of energy over the course of a year based on the amount of solar radiation it receives. As the use increases, more energy is required and the percentage coming from the collector lessens. This is especially true during winter months, when the demand is greater because the mains water temperature is lower and less solar radiation is available.

4.4 Gas Storage Water Heater

Gas storage water heaters behave very similarly to electric storage water heaters. However, they have lower efficiencies because of higher tank losses (caused partly by the central flue) and the combustion efficiency of gas (see Figure 35 and Figure 36). The same trends of higher efficiency with higher use, and an increase or decrease in energy consumption in unconditioned space depending on whether the climate is heating or cooling dominated, are seen for gas storage water heaters. In the case of a gas water heater in Atlanta in unconditioned space, a dip in efficiency in the unconditioned space leads Los Angeles to have a higher efficiency. The delivered energy is nearly identical in both cases, but Atlanta has higher tank losses because the water heater is located in an unconditioned basement.

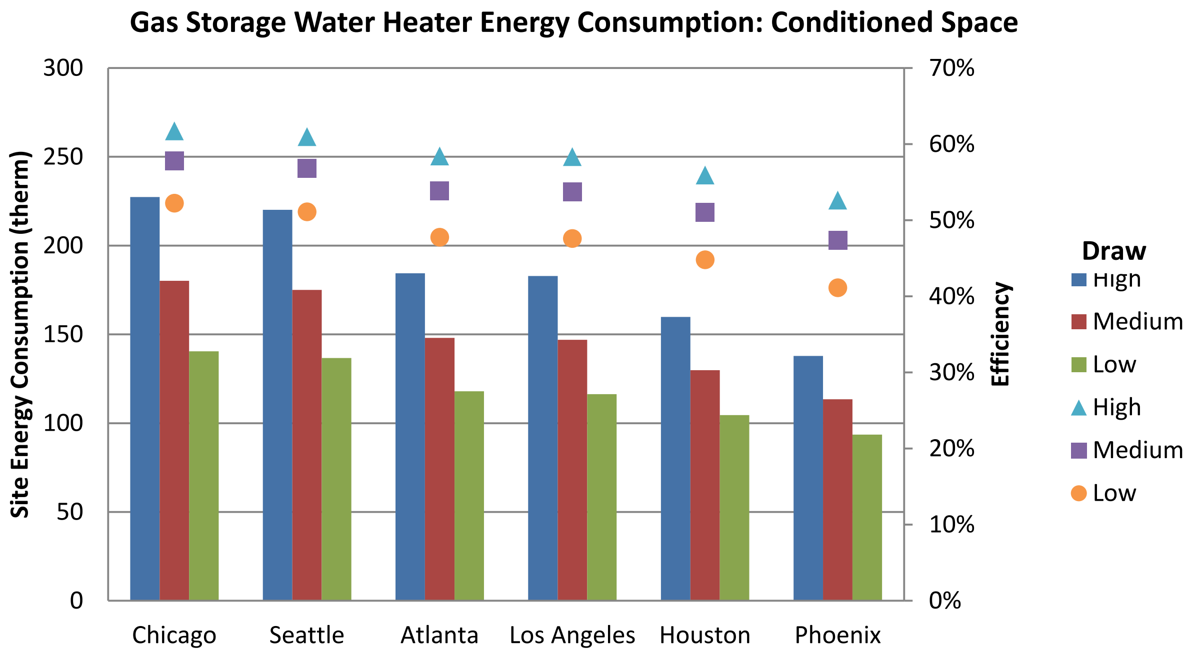

Figure 35. Gas water heaters in conditioned spaces—annual energy consumption

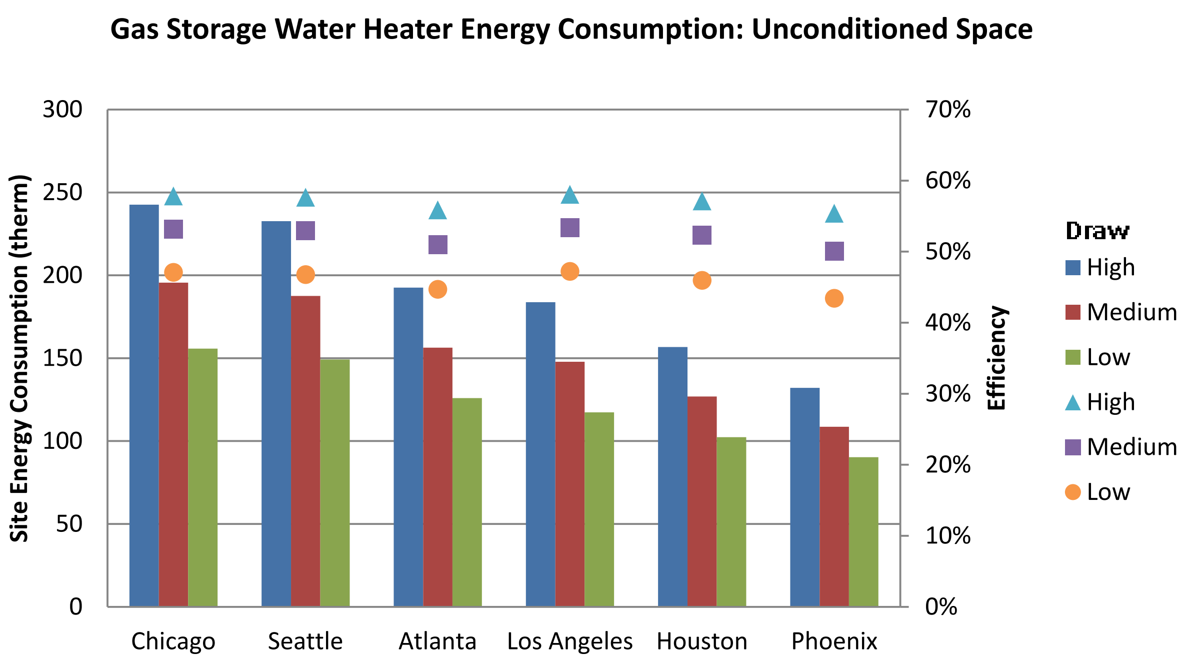

Figure 36. Gas water heaters in unconditioned spaces—annual energy consumption

4.5 Gas Tankless Water Heater

For tankless water heaters, the efficiency is primarily a function of the daily draw profile and the spacing of draws. Higher use situations have more draw events, which lead to higher efficiencies at higher draw volumes. However, the annual draw volume is a less significant factor for overall efficiency than for storage water heaters (see Figure 37). This is because there are no standby losses during periods when the water heater is idle, although there are losses from the water heater to ambient air during and after draws. There are also cycling losses from heating the relatively massive heat exchanger. These losses can be significant for short draws where little heat from the burner actually goes into the water.

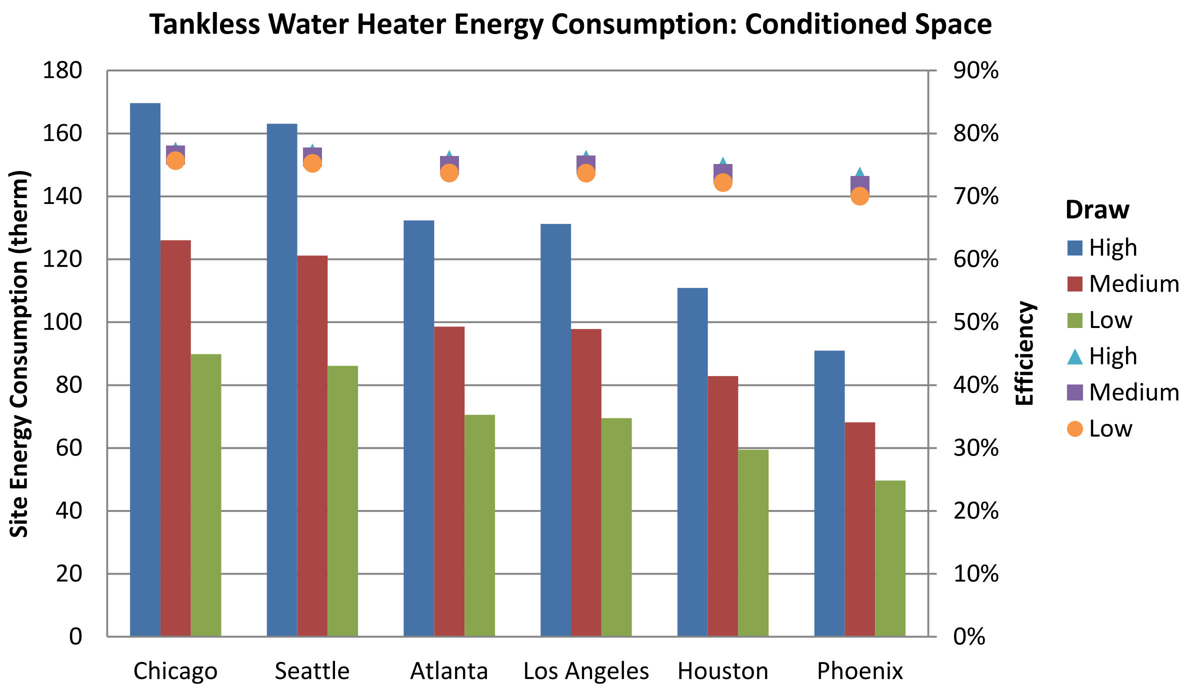

Figure 37. Tankless water heaters in conditioned spaces—annual energy consumption

In unconditioned space a few other factors are in play (see Figure 38). For one, the warmer ambient air temperature in unconditioned spaces in hot climates can reduce the losses associated with the heating and cooling of the heat exchanger. Freeze protection energy can also have an impact on overall energy consumption. Freeze protection was required in Chicago (basement), Houston (garage), and Phoenix (garage), although the amount of energy consumed in Phoenix and Houston was very small. Freeze protection was not required in Seattle (basement), Atlanta (basement), and Los Angeles (garage). In general, freeze protection never consumed more than 1% of the total site energy consumed by the tankless water heater.

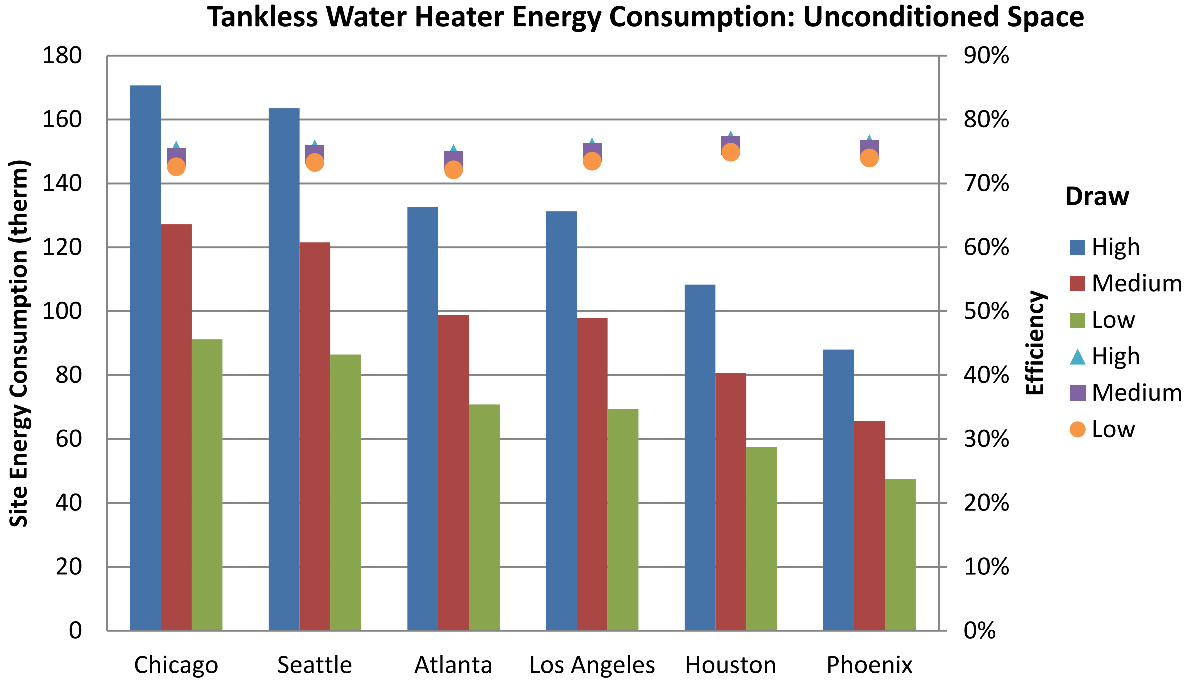

Figure 38. Tankless water heaters in unconditioned spaces—annual energy consumption

4.6 Condensing Water Heater

The behavior of condensing water heaters is very similar to that of gas storage water heaters (see Figure 39 and Figure 40). The efficiency is largely a function of the use, leading to higher efficiencies with higher use draw profiles. Efficiency is more strongly a function of mains temperature because the combustion efficiency is impacted by the average tank temperature. Condensing water heaters are more efficient than regular gas storage water heaters for two reasons: (1) the conversion efficiency is higher because latent heat is recovered from the flue gas (in this case, the conversion efficiency is generally 92%–96%, depending on the average tank temperature); and (2) standby losses are lower because the vertical flue in the center of the tank is replaced by the condensing heat exchanger. This leads to a much higher annual efficiency than can be achieved by a typical gas storage water heater.

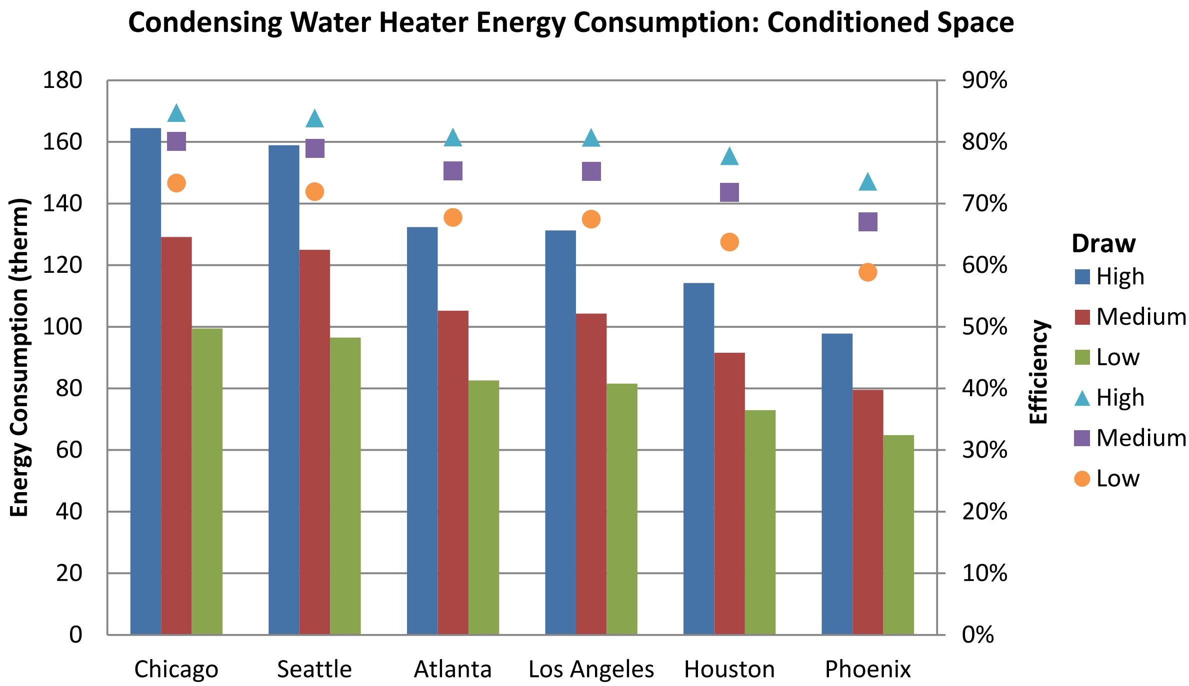

Figure 39. Condensing water heaters in conditioned spaces—annual energy consumption

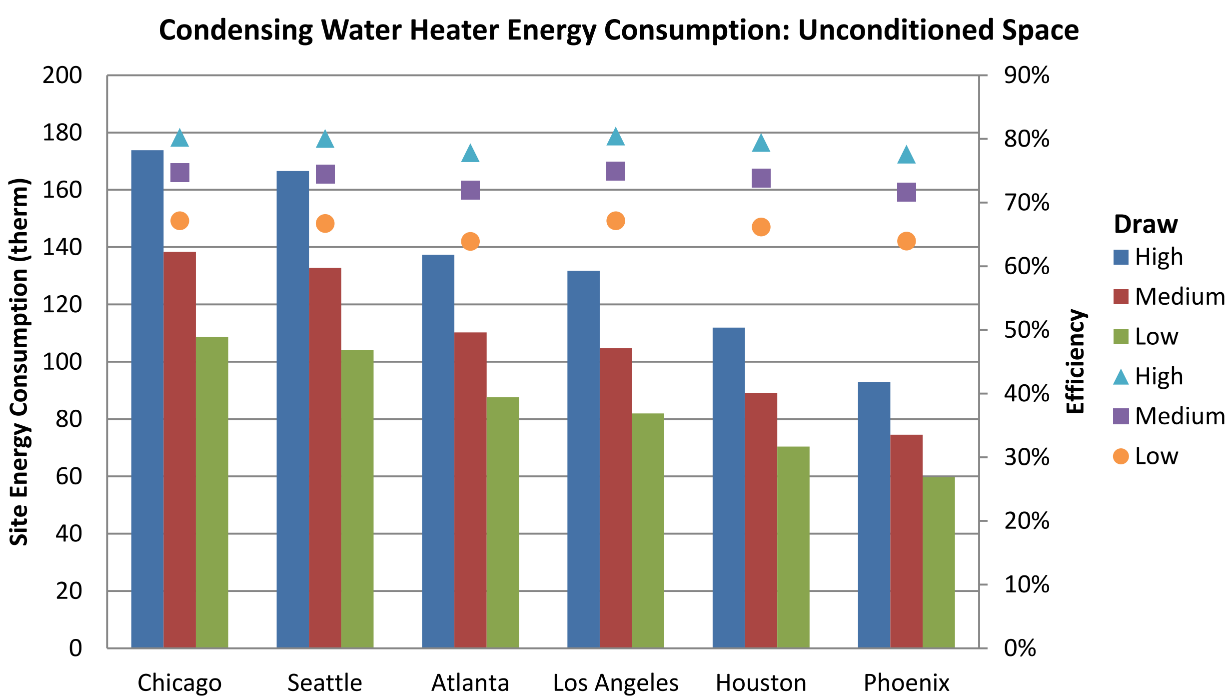

Figure 40. Condensing water heaters in unconditioned spaces—annual energy consumption

4.7 Solar Water Heater With Gas Backup

For a solar water heater with gas backup, the results are different than for one with electric backup. The solar water heater with gas backup is a two-tank system consisting of a solar preheat tank in series with a standard gas storage water heater. This leads to much higher standby losses, which lead to increased gas consumption and lower annual efficiency than a solar water heater with electric backup. In addition, the backup gas water heater has a standing pilot that consumes 450 Btu/h, leading to a minimum energy consumption by the storage tank of 39.4 therm/yr. For the low-use case in Phoenix, most of the energy use is the pilot light energy consumption. In many cases pilot light energy consumption is useful as it offsets standby losses; however, this is not always true, especially when the tank is used as a backup for a solar water heater. When a gas water heater is in hot unconditioned space, such as a garage in Phoenix or Houston, the temperature difference between the tank and the ambient air may be small enough that the tank losses are smaller than the amount of heat added to the tank by the pilot light. This causes the pilot light to heat the tank above its set point temperature, increasing the losses and wasting some energy. If a large volume of hot water comes into the tank from the solar storage tank, this hot water may heat the tank above its set point temperature. In this case, the pilot light energy is not entirely useless; it will slow the decay of tank temperature, but it increases standby losses, wasting some energy. The net impact of the pilot light leads to cases in Phoenix having a lower efficiency than the single tank solar electric water heater (see Figure 41 and Figure 42). This pilot light energy waste also causes the low-use cases to have lower efficiency than the higher use cases, which is the opposite of the trend seen for the single-tank solar electric water heater. Appendix B includes a detailed discussion of the pilot light and its impact on the energy consumption of gas water heaters.

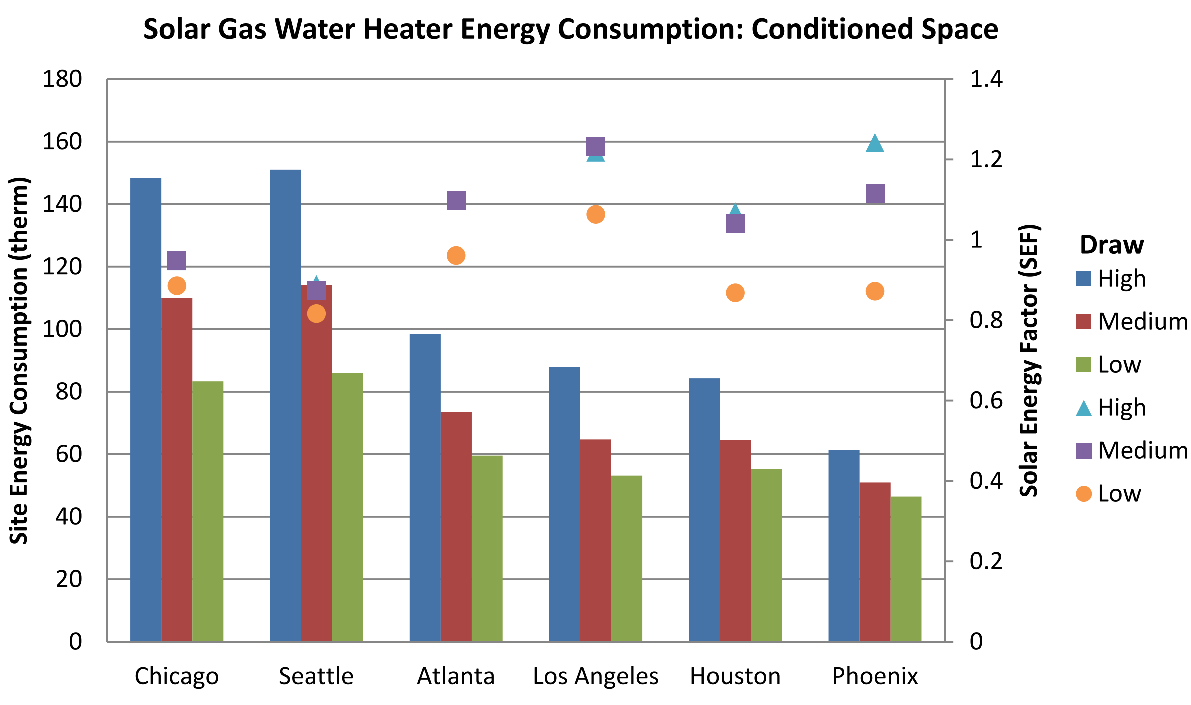

Figure 41. Solar water heaters with gas backup in conditioned spaces—annual energy consumption

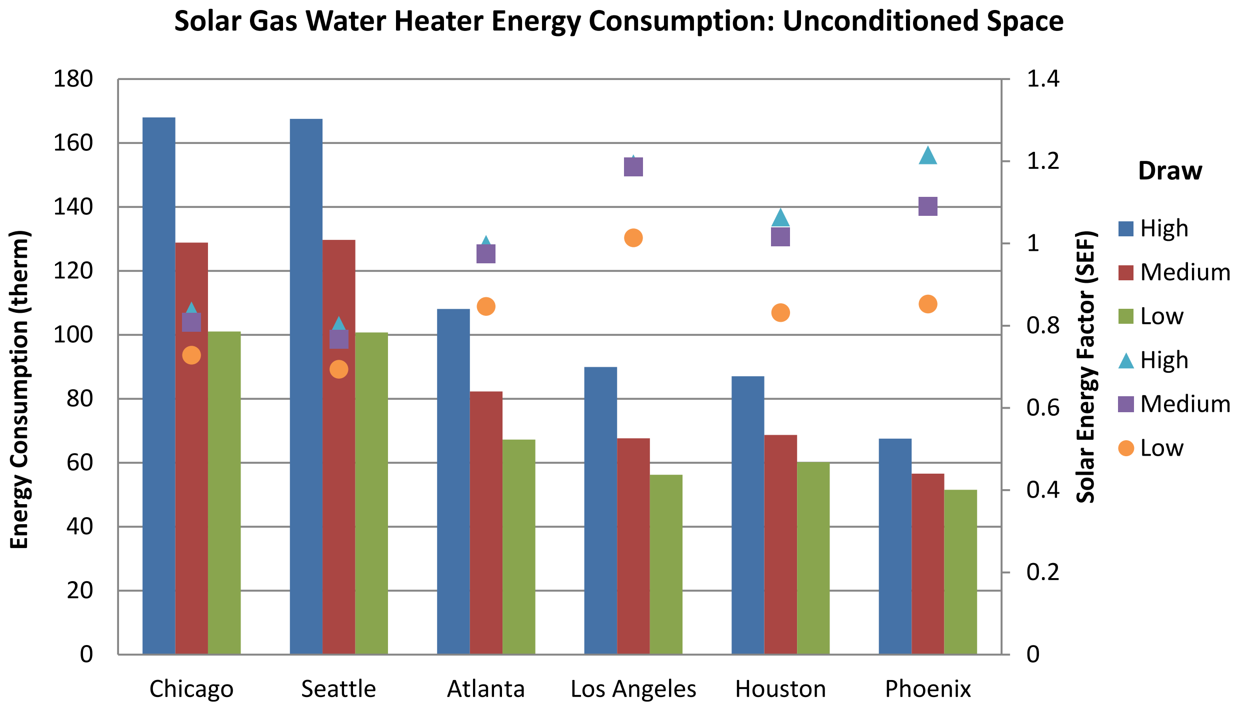

Figure 42. Solar water heaters with gas backup in unconditioned spaces—annual energy consumption

4.8 Comparison of Electric Water Heaters

When comparing water heaters, changes in space heating, cooling, and air handler fan energy consumption, as well as the outlet temperature normalization energy, are taken into account, as is any secondary energy consumption (for example, the energy consumed by the pump on the collector loop for solar water heaters). Because electric water heaters are assumed to be installed in homes without gas service and have an ASHP instead of a furnace/AC, gas and electric water heaters are not directly compared here. The electric water heater that uses the least amount of source energy in each case is shown in Table 5. In general, solar water heaters are the most energy-efficient option for low users of hot water (for the fixed collector area used in this analysis) as the SEF (efficiency) is greater at low use. However, highest efficiency does not necessarily translate into cost effectiveness, as low hot water use means low savings potential. Solar water heaters are also a better option in unconditioned spaces, where HPWHs tend to be less efficient than in conditioned spaces. This is true in all locations except Seattle, which has very little sun and therefore a low SEF and higher water heater energy consumption. If the solar water heating system size were increased, solar would save the most source energy in all locations, as a larger system would meet a larger load. However, such a system would not be cost effective and the system sizes chosen here are representative of the typical size of a solar water heater in the United States.

In conditioned spaces for medium and high draw profiles, HPWHs often save more energy than solar water heaters. The HPWH provides net cooling in all climates, which is beneficial in warm climates. The solar water heater always provides net heating through losses in the pipes connecting the collector to the tank and higher tank losses from the higher storage temperature. This is a detriment in cooling-dominated climates, which helps make HPWHs more attractive than solar water heaters in warm climates.

Table 5. Electric Water Heating Option with the Lowest Source Energy Use

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Solar Electric	Solar Electric	HPWH	Solar Electric	Solar Electric	Solar Electric
Seattle	Solar Electric	HPWH	HPWH	Solar Electric	HPWH	HPWH
Atlanta	Solar Electric	Solar Electric	HPWH	Solar Electric	Solar Electric	Solar Electric
Los Angeles	Solar Electric	Solar Electric	Solar Electric	Solar Electric	Solar Electric	Solar Electric
Houston	Solar Electric	HPWH	HPWH	Solar Electric	Solar Electric	Solar Electric
Phoenix	Solar Electric	HPWH	HPWH	Solar Electric	Solar Electric	Solar Electric

Yellow denotes no option is within 10% of using the same amount of source energy and green denotes one other option within 10%

Table 6 and Table 7 provide the source energy savings of the advanced electric water heating technologies relative to the base case (electric storage). Savings are provided as percentages and as absolute values to demonstrate the impact of the variable water heating load on annual savings. For HPWHs, the percent energy savings is highest in the medium use cases. This is because medium-use cases have the highest efficiency, as the draw volume is large enough that tank losses have a smaller impact on the HPWH efficiency. The volume is not so high, however, that the electric resistance element needs to be used frequently. However, the absolute source energy savings is always largest in high-use cases because the demand is greater. HPWHs also generally perform best in conditioned spaces, except in the marine climates of Seattle and Los Angeles. Seattle has the longest heating season and shortest cooling season of any of the locations, so the heat pump provides a space conditioning penalty for most of the year; thus, it has the largest net penalty of any location. In Los Angeles, the HPWH has roughly the same net energy consumption in conditioned and unconditioned spaces. However, the tank losses in unconditioned spaces are higher than in conditioned spaces, so the electric resistance water heaters perform slightly better in conditioned spaces. As a result, the net savings for HPWHs in Los Angeles are higher for unconditioned spaces than for conditioned spaces.

Table 6. Percent Source Energy Savings of Each Electric Water Heater Versus the Base Case

Water Heater Installation Location		HPWH Conditioned	HPWH Unconditioned	Solar Electric Conditioned	Solar Electric Unconditioned
Chicago	Low	42%	33%	51%	51%
	Medium	43%	33%	43%	44%
	High	37%	28%	35%	35%
Seattle	Low	40%	44%	46%	47%
	Medium	40%	44%	38%	39%
	High	34%	37%	31%	32%
Atlanta	Low	57%	54%	69%	69%
	Medium	59%	55%	62%	62%
	High	52%	48%	52%	51%
Los Angeles	Low	50%	51%	75%	75%
	Medium	52%	53%	67%	67%
	High	46%	46%	56%	56%
Houston	Low	64%	53%	67%	69%
	Medium	68%	56%	63%	64%
	High	62%	51%	54%	55%
Phoenix	Low	61%	49%	79%	81%
	Medium	64%	52%	75%	77%
	High	61%	48%	68%	69%

Table 7. Source Energy Savings of Each Electric Water Heater Versus the Base Case

Water Heater Installation Location		HPWH Conditioned	HPWH Unconditioned	Solar Electric Conditioned	Solar Electric Unconditioned
Chicago	Low	12.2	10.1	14.6	15.6
	Medium	16.8	13.4	17.0	17.9
	High	19.1	14.7	18.1	18.8
Seattle	Low	11.0	12.8	12.8	13.6
	Medium	15.3	17.3	14.5	15.3
	High	17.0	19.0	15.5	16.3
Atlanta	Low	13.1	12.9	16.1	16.6
	Medium	18.2	17.5	19.4	19.7
	High	21.2	19.8	20.9	21.3
Los Angeles	Low	11.5	12.0	17.1	17.6
	Medium	16.2	16.6	20.6	21.0
	High	18.7	18.8	22.5	22.8
Houston	Low	12.7	10.6	13.4	13.9
	Medium	18.1	14.9	16.7	17.1
	High	21.3	17.5	18.5	18.9
Phoenix	Low	10.5	8.3	13.6	13.6
	Medium	14.4	11.4	16.9	17.0
	High	17.6	13.7	19.5	19.6

For solar water heaters, Atlanta and Los Angeles have the highest absolute energy savings potential. Both cities have a moderate solar resource and a lower mains water temperature, which lead to higher demand than in hot climates. The solar resource is much higher in Phoenix, but the high mains temperature reduces the use and thus the absolute savings potential and increases the savings potential as a percent of the base case water heater energy consumption. The solar storage tank has more insulation than the base case electric water heater, leading to lower overall tank losses and higher performance in the unconditioned space cases in cold climates. In addition, when a solar water heater is installed in an unconditioned space in a location with a basement (Chicago, Seattle, and Atlanta), the collector piping that is inside the home is assumed to be in conditioned space, so the solar water heater does provide some beneficial space heating.

4.9 Comparison of Gas Water Heaters

Changes in space heating, cooling, air handler fan energy consumption, and outlet temperature normalization energy are taken into account in this comparison. For gas water heaters, solar water heaters almost always save the most source energy. The gas water heater with the lowest source energy use in each case is shown in Table 8. The only cases where solar water heaters do not use the least amount of source energy are for low use in conditioned spaces in cooling-dominated locations (Phoenix and Houston). Solar water heaters have high losses because the tanks and the pipes connecting the collectors to the solar preheat tanks lose heat and storage tank temperatures are higher. Tankless water heaters have the smallest impact on space heating and cooling loads because they have losses only while they are operating (from smallest to largest, the impact on space heating and cooling for gas water heaters is tankless, condensing, gas storage, then solar). This impact on space conditioning equipment is significant enough to give tankless water heaters an energy savings advantage in conditioned space in low-use cases where the water heating loads—and therefore potential savings—are small. In the case of high use in conditioned space in Seattle, a condensing water heater comes within 10% of being the most efficient gas water heater. This is due to the poor solar resource in Seattle, the efficiency of the condensing water heater, and the benefit of the tank losses from the condensing water heater. However, if the solar water heater in Seattle were larger, it would provide enough savings that a condensing water heater would not come within 10% of providing the most savings.

Table 8. Gas Water Heating Option With the Lowest Source Energy Use

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Seattle	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Atlanta	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Los Angeles	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Houston	Tankless	Solar Gas	Solar Gas	Solar Gas	Solar Gas	Solar Gas
Phoenix	Tankless	Tankless	Solar Gas	Solar Gas	Solar Gas	Solar Gas

Yellow denotes no option is within 10% of saving the same amount of source energy and green denotes one other option within 10%

Table 9 and Table 10 provide the source energy savings of the advanced gas water heating technologies relative to the base case (gas storage). Savings are once again provided as percentages and as absolute values to demonstrate the impact of the variable water heating loads on annual savings. For tankless water heaters, the magnitude of the savings is relatively independent of the draw volume for any given location. This is because outlet temperature normalization energy consumption for the tankless water heater increases at higher draw volumes and effectively negates the additional energy savings associated with higher draw volumes. In actual use, normalization energy does not exist and homeowners may change their behavior to ensure that they get water at a useful temperature. For example, with a tankless water heater a homeowner may draw hot water from sinks at a higher flow rate because of the minimum flow rate required for the burner to fire. As a result, the normalization energy impact seen here may not occur in homes as the change in behavior may not lead to a significant increase in annual energy consumption (51). When a tankless water heater is in conditioned space, changes in the space heating and cooling energy consumption have a significant impact, so it saves the most energy in hot climates where the significantly reduced heat losses to ambient are beneficial and vice versa. In unconditioned space, the reduction in tank losses and decreased potential to save energy because of higher mains temperatures cause the value of the savings to decrease in warmer locations.

Table 9. Percent Source Energy Savings of Each Gas Water Heater Versus the Base Case

Water Heater Installation Location		Tankless		Condensing		Solar Gas	
		Cond	Uncond	Cond	Uncond	Cond	Uncond
Chicago	Low	18%	27%	20%	23%	34%	40%
	Medium	14%	22%	21%	23%	34%	38%
	High	12%	18%	21%	23%	31%	34%
Seattle	Low	13%	27%	21%	23%	33%	43%
	Medium	10%	21%	21%	23%	31%	38%
	High	8%	17%	21%	23%	28%	34%
Atlanta	Low	27%	31%	20%	22%	41%	42%
	Medium	21%	24%	21%	22%	44%	44%
	High	16%	19%	21%	22%	42%	42%
Los Angeles	Low	27%	28%	20%	21%	41%	45%
	Medium	21%	22%	21%	22%	44%	49%
	High	16%	17%	21%	22%	42%	47%
Houston	Low	41%	27%	20%	21%	23%	34%
	Medium	32%	21%	22%	21%	33%	39%
	High	25%	17%	22%	21%	34%	39%
Phoenix	Low	43%	29%	19%	22%	17%	35%
	Medium	34%	22%	20%	22%	26%	40%
	High	27%	17%	21%	21%	31%	42%

Table 10. Source Energy Savings (MMBtu) of Each Gas Water Heater Versus the Base Case

Water Heater Installation Location		Tankless		Condensing		Solar Gas	
		Cond	Uncond	Cond	Uncond	Cond	Uncond
Chicago	Low	2.8	4.6	3.1	4.0	5.3	6.8
	Medium	2.8	4.7	4.1	5.0	6.7	8.1
	High	2.9	4.7	5.2	6.2	7.7	9.1
Seattle	Low	1.9	4.4	3.1	3.7	4.9	7.0
	Medium	1.9	4.3	4.0	4.7	5.9	7.8
	High	1.9	4.3	5.1	5.9	6.8	8.6
Atlanta	Low	3.4	4.2	2.6	3.0	5.3	5.8
	Medium	3.3	4.1	3.4	3.8	7.1	7.5
	High	3.3	4.0	4.3	4.7	8.5	8.8
Los Angeles	Low	3.4	3.6	2.6	2.7	5.3	5.8
	Medium	3.3	3.6	3.4	3.5	7.1	7.9
	High	3.3	3.5	4.3	4.4	8.5	9.4
Houston	Low	4.7	3.0	2.3	2.4	2.6	3.8
	Medium	4.6	2.9	3.1	2.9	4.6	5.5
	High	4.4	2.9	3.9	3.7	6.0	6.7
Phoenix	Low	4.4	2.9	2.0	2.2	1.7	3.5
	Medium	4.2	2.7	2.5	2.6	3.2	4.8
	High	4.1	2.5	3.2	3.1	4.7	6.1

For condensing water heaters, the savings as a percentage of the total source energy savings is relatively constant across all locations, usage patterns, and installation locations. Savings result from the higher tank insulation of a condensing water heater and the higher combustion efficiency. Because the savings potential is relatively constant across climates, it can be concluded that mains water temperature does not have a significant impact on the combustion efficiency, as any large impact would cause the percent savings to change across climates. This is because the water temperature next to the condensing heat exchanger stays relatively constant. For the condensing heat exchanger to be completely exposed to mains water, most hot water in the tank must be drawn before recovery can occur.

The solar water heater savings are very dependent on climate. As was true in the solar water heater with electric backup case, the highest absolute savings are found in moderate climates, which have both moderate loads and solar resource. However, the value of the savings is also large in colder climates because of the higher demand. In additional, the higher thermal losses from the two tanks and collector piping have a positive impact on the space conditioning energy consumption in colder climates if the water heater is installed in unconditioned space. For all solar water heaters installed in basements (Chicago, Seattle, and Atlanta), the first 20 feet of collector piping is assumed to be in conditioned space, so the solar water heater does provide some beneficial space heating as well. Although the solar resource is large in Houston and Phoenix, the low load leads to reduced savings potential. The tank losses and wasted pilot light energy are also a larger percentage of the total energy consumption in low use cases. For water heaters in conditioned spaces in these locations, the higher tank losses of solar water heaters lead to a further reduction in energy savings because of their impact on space conditioning equipment, especially in low-use cases.

5 Economic Analysis

Two economic metrics were used to evaluate these technologies: Life Cycle Cost (LCC) and breakeven cost. LCC is the total cost of installing, operating, and maintaining each water heater for the entire analysis period (in this case, 13 years, which is the typical lifetime of a gas or electric storage water heater), with future cash flows discounted to their present value. Breakeven cost is what the capital cost of any of the more efficient technologies examined here would need to be for that system to have the same LCC as the baseline (gas or electric storage). A simple way of thinking of these two metrics is that LCC evaluates the technologies available today and breakeven cost shows where they need to be in terms of net installed cost to be cost effective in the future. New construction and retrofit cases are considered here, although only capital costs change for these two options. For retrofit cases, the current water heaters are assumed to have no remaining useful lifetime and replacements are necessary. Cases with and without incentives are considered here. When looking at the impact of incentives, there are three cases: no incentives, federal incentives only, and both federal and local incentives. The federal only case is necessary because local incentives will not apply to the entire climate zone represented by each city. This section is divided into subsections covering capital costs, maintenance costs, annual operating costs, and finally, LCCs and breakeven costs.

5.1 Water Heater Capital Costs

The capital cost for each type of water heater consists of two major components: the actual equipment cost and the installation cost. Several sources were examined to determine capital costs. One major source is the 2010 federal rule on residential water heater efficiency (7). This ruling set updated minimum efficiency standards for residential water heaters starting in 2015. As part of this ruling, the costs of all water heating technologies except solar were evaluated. These cost projections included detailed, itemized installation costs for new and retrofit cases. This was the main source of installation cost information.

Equipment costs for each technology were determined from a mix of the 2010 federal rulemaking and looking at retailers for the price they typically sell each water heater. For condensing water heaters, the federal rulemaking had a significantly lower equipment cost than what may be typical of the equipment available today. The model used for this analysis is based on a very expensive high-efficiency unit, as this was the only unit with sufficient data available to create a fully validated model. This leads to slightly higher performance than a typical unit. To more accurately represent a typical condensing water heater cost, the equipment cost was based on a more typical unit. This unit is not carried in “big box” stores currently, so the price from niche suppliers was used. The equipment cost, net installed cost, and source of cost are provided in Table 11.

Table 11. Equipment and Net Installed Costs for Different Water Heating Technologies

Water Heater Type	Equipment Cost	New Construction Net Installed Cost	Retrofit Net Installed Cost	Cost Sources
Gas Storage	$450	$1,329	$968	DOE* Rulemaking (7)
Gas Tankless	$1,109	$1,915	$2,458	DOE Rulemaking (7)
Gas Storage Condensing	$1,633	$2,252	$2,562	Niche Suppliers (52) (53) (54), DOE Rulemaking (7)
Electric	$283	$467	$598	DOE Rulemaking (7)
HPWH	$1,169	$1,414	$1,622	DOE Rulemaking (7)
Solar Gas	$3,466	$7,530	$7,530	California Solar Initiative (10)
Solar Electric	$3,016	$6,982	$6,982	California Solar Initiative (10)

* DOE = U.S. Department of Energy

Solar water heaters are not considered as part of the federal rulemaking process, so a separate source was required to determine their average installed costs. In this case, data provided by the California Solar Initiative (10) were used. These data provide the installed costs of many solar water heating systems and the size of each system. For this work, the average costs of gas and electric solar water heaters were based on the average costs of direct, forced circulation systems with a collector area of 60–66 ft^2, the correct backup fuel source, and the same number of tanks (one for electric, two for gas) with approximately the same volume as what was modeled here. These data include new construction and retrofit installations, but there were not enough new construction installations to differentiate new construction and retrofit costs.

Although these data provide a good source for determining the average installed cost of a solar water heater, all the installations are in California. Average labor costs vary by state, so to determine a national average installed cost, the net installed cost must be subdivided into labor costs and material costs. RSMeans cost books were used to determine the material costs and the average labor markup for California (55). The average material costs were $3,466. Based on the cost and the description in the cost books, this was assumed to be the material cost for a two-tank system. For a single-tank system, the material cost was assumed to be the two-tank system material cost minus the equipment cost of a gas water heater. The remaining portion of the installed cost is assumed to be subject to the labor markup for California (1.297—the national average labor markup is 1.000). The labor cost from the California Solar Initiative data was then divided by the labor markup to get a national average installed cost. The results of these calculations are summarized in Table 12. In addition to comparing the LCCs with these national average installed costs for solar water heaters, the hypothetical scenario of low-cost solar water heating (with an installed cost of $3000/system) is examined in Appendix E. This hypothetical installed cost is a goal for research and development efforts underway at the National Renewable Energy Laboratory (22).

Table 12. Solar Water Heater Net Installed Cost Determination

Backup Fuel	Number of Sites	Average California Installed Cost	Materials Cost	Labor Costs	California Labor Markup	National Average Installed Cost
Electricity	36	$8,026	$3,016	$5,010	1.297	$6,879
Gas	18	$8,871	$3,466	$5,405	1.297	$7,633

The DOE water heater rulemaking and its technical support documents were used to determine the installation cost of the non-solar water heaters (7). This rulemaking applies cost drivers that may apply to certain homes (for example, additional labor if a water heater is installed in an attic). Data from the 2005 Residential Energy Consumption Survey were then used to determine how many homes would have each cost driver applied to them. The final installation costs derived from this procedure are provided in Table 13. For the full details about how the installation costs were determined and what cost drivers are applicable to each technology, refer to Appendix F. Note that gas storage water heaters are cheaper to install in retrofit scenarios, as there are significant costs associated with installing the venting in new construction cases.

Table 13. Installation Costs for Non-Solar Water Heaters

Water Heater	Gas Storage	Tankless	Condensing	Electric Storage	HPWH
New Construction	$879	$806	$598	$184	$245
Retrofit	$518	$1,342	$801	$315	$453

Incentives are another key factor in capital costs. Cases with no incentives, federal incentives, and federal plus local incentives are considered here. Current federal incentives apply only to solar water heaters and cover 30% of the installed cost of a solar water heating system. Local incentives are shown in Table 14. For local incentives, the provider is also listed to show where the incentive is applicable. Local incentives were taken from the Database of State Incentives for Renewable Energy (56), which gives all local incentives, even for programs that may currently be closed for lack of funding. Atlanta has the largest incentives, but most are available only for homes within the city limits (not the suburbs). Tax credits and rebates are applied in slightly different ways. Because it would take about a year to actually see the value of a tax credit, all tax credits are applied one year after purchase and therefore are slightly discounted. Rebates are applied instantly to the net installed cost and are not discounted.

Table 14. Local Incentives for Various Water Heating Technologies

Location	Water Heater	Local Incentive Provider	Incentive Type	Value
Atlanta	HPWH	City of Atlanta	Rebate	$1,000
	Tankless	City of Atlanta	Rebate	$500
	Condensing	City of Atlanta	Rebate	$200
	Solar	City of Atlanta	Rebate	$1,500
	HPWH	Georgia Power	Rebate	$250
	Solar	Georgia Power	Rebate	$250
	Solar	State	Tax Credit	35% up to $2,500
Chicago	Solar	State	Rebate	30% of installed cost
Los Angeles	Solar Gas	State	Tax Credit	$1,875
	Solar Electric	State	Tax Credit	$1,089
	Tankless	SoCalGas	Rebate	$150 (retrofit only)
	HPWH	SCE	Rebate	$30
Phoenix	Solar	State	Tax Credit	25% up to $1,000
	Solar	APS	Rebate	$0.50/kWh of first year savings up to 50%
Seattle	HPWH	Puget Sound Energy	Rebate	$500 (unconditioned space only)

5.2 Water Heater Maintenance Costs

All these technologies require annual maintenance to perform optimally. It is especially important to consider maintenance here as no annual performance degradation is considered in this analysis, meaning that maintenance is assumed to keep the equipment operating like new throughout its lifetime. The 2010 federal rulemaking includes maintenance costs as well as the likelihood that a homeowner will actually perform the necessary maintenance. For this analysis, all maintenance costs were annualized by multiplying the cost by the likelihood that it would be performed and dividing by the maintenance period. Applying the maintenance cost in this way ensures they are applied to all water heaters and takes into account that some people may not properly maintain their equipment. Solar water heater maintenance costs came from a DOE publication providing an overview of solar water heating systems (57). It assumes that all homeowners will maintain the solar water heaters and that maintenance is done by a professional. In the case of homeowner maintenance, the costs may be significantly lower; however, most homeowner will be unable to perform maintenance on many of these technologies. The solar water heater maintenance costs came from a paper written in 1996 (57) and are escalated to current value. The maintenance costs used here are provided in Table 15.

Table 15. Maintenance Costs for Different Water Heating Technologies

Water Heater	Maintenance Description	Cost	Period (years)	% likelihood	Annual Cost
Gas	Annual Flush	$124.57	1	10%	$12.46
Gas Tankless	De-liming	$71.71	1	56%	$40.16
Condensing	Annual Flush	$124.57	1	10%	$12.46
Electric	Annual Flush	$123.05	1	10%	$12.31
HPWH	Heat Pump Maintenance	$94.50	5	27%	$17.41
	Annual Flush	$123.05	1	10%	
Solar Gas	Total Maintenance	$43.00	1	100%	$55.46
	Backup Tank Annual Flush	$124.57	1	10%	
Solar Electric	Total Maintenance	$43.00	1	100%	$43.00

5.3 Annual Operating Costs

Monthly energy consumption was used to determine annual operating costs, taking into account seasonal variations in energy costs. All water heaters have some seasonal variations in energy use, as hot water use changes with mains water temperature, but several technologies, including solar and HPWHs, are even more sensitive to seasonal changes in rates. Savings are higher during the summer. Energy consumption was calculated in the same manner as when technologies were compared in Sections 4.8–4.9 and takes into account changes in space conditioning energy consumption, outlet temperature normalization energy, and water heater energy consumption. Table 16 and Table 17 show monthly rates for gas and electricity at each location. These are based on the rates for the largest utility at each location. The rates used here are from an economic analysis of solar water heaters (58). These rates are based on 2008 data from the Energy Information Agency (59) and reflect the average residential rate paid for each utility. Given that rates are volatile (especially natural gas rates), current rates may be different than shown used here. As these rates reflect the actual rate paid by utility customers, tiered rates are accounted for.

Table 16. Monthly Gas Rates in $/Therm

Location	Atlanta	Chicago	Houston	Los Angeles	Phoenix	Seattle
Utility	Austell Natural Gas	Nicor Gas	Atmos Energy	Southern California Gas	Southwest Gas	Puget Sound Energy
January	$1.26	$0.84	$1.02	$1.11	$1.61	$1.20
February	$1.35	$0.90	$1.18	$1.15	$1.63	$1.20
March	$1.47	$1.01	$1.19	$1.16	$1.72	$1.22
April	$1.67	$1.12	$1.62	$1.31	$1.85	$1.20
May	$2.06	$1.35	$1.70	$1.45	$2.07	$1.27
June	$2.41	$1.60	$2.09	$1.52	$2.16	$1.34
July	$2.47	$1.92	$2.23	$1.66	$2.40	$1.47
August	$2.54	$1.90	$1.85	$1.48	$2.48	$1.53
September	$2.43	$1.62	$1.87	$1.28	$2.41	$1.44
October	$1.75	$1.26	$1.51	$1.17	$2.21	$1.32
November	$1.39	$1.11	$1.15	$0.95	$1.94	$1.40
December	$1.39	$0.92	$1.09	$0.93	$1.70	$1.39
Average	$1.85	$1.30	$1.54	$1.26	$2.02	$1.33

Table 17. Monthly Electricity Rates in $/kWh

Location	Atlanta	Chicago	Houston	Los Angeles	Phoenix	Seattle
Utility	Georgia Power	Commonwealth Edison	TXU Energy	Southern California Edison	Arizona Public Service	Puget Sound Energy
January	$0.00884	$0.00998	$0.01199	$0.01494	$0.00937	$0.00931
February	$0.00905	$0.01032	$0.01176	$0.01452	$0.00955	$0.00941
March	$0.00951	$0.01090	$0.01236	$0.01429	$0.00994	$0.00936
April	$0.00966	$0.01150	$0.01281	$0.01403	$0.01061	$0.00935
May	$0.00994	$0.01211	$0.01323	$0.01469	$0.01168	$0.00891
June	$0.01121	$0.01209	$0.01376	$0.01566	$0.01172	$0.00959
July	$0.01140	$0.01192	$0.01444	$0.01558	$0.01160	$0.00967
August	$0.01136	$0.01174	$0.01420	$0.01573	$0.01151	$0.00969
September	$0.01088	$0.01215	$0.01386	$0.01517	$0.01126	$0.00975
October	$0.01052	$0.01257	$0.01390	$0.01419	$0.01108	$0.00969
November	$0.00981	$0.01278	$0.01367	$0.01535	$0.01011	$0.00966
December	$0.00946	$0.01129	$0.01351	$0.01492	$0.01017	$0.00940
Average	$0.01014	$0.01161	$0.01329	$0.01493	$0.01072	$0.00948

5.4 Life Cycle Costs

The LCC analysis performed here was done in accordance with Federal Energy Management Program guidelines (60). The simplified LCC cost equation, "for computing the LCC of energy and water conservation projects in buildings" (60) is given in Equation 5.

$$LCC = I + Repl - Res + E + W + OM\&R \quad (5)$$

where,

I	=	the investment costs,
$Repl$	=	the replacement costs,
Res	=	the residual value (scrap, resale, or salvage),
E	=	the energy costs,
W	=	the water costs, and
$OM\&R$	=	the nonfuel operating, maintenance, and repair costs.

All costs are converted to present value using a 3% discount rate, which is in line with current federal guidelines (61). Fuel escalation costs were assumed to equal inflation in this case. Water costs were assumed to be the same in all cases (when comparing at the same draw profile) and excluded from the LCC calculations. Even though the volume of hot water drawn may change, the mixed draw volume is constant, leading to constant water use for each draw profile.

To determine the present value of annually recurring costs (fuel consumption and maintenance for most water heaters), the uniform present value (UPV) factor is applied to these costs. The UPV can be defined (Equation 6) as:

$$UPV = \frac{(1+d)^n - 1}{d(1+d)^n} \quad (6)$$

where,

d	=	the discount rate (3%) and
n	=	the length of the study period.

For nonrecurring costs (maintenance costs for a HPWH and residual value of water heaters with a lifetime longer than 13 years) the present value is calculated using the single present value (SPV), which is defined (Equation 7) as:

$$SPV = \frac{1}{(1+d)^t} \quad (7)$$

where,

t	=	the time (in years) when the cost occurs.

For most cases, the water heater life is 13 years (hence why it was chosen as the analysis period), so there is no residual value. However, tankless water heaters and solar water heaters are assumed to last longer than 13 years (20 and 30 years, respectively), and therefore do have a residual value. In these cases, the residual value was calculated (Equation 8) as:

$$Res = \frac{(y-n)}{y} I \cdot SPV \tag{8}$$

where,

y = the expected lifetime of the system.

This devalues the equipment linearly, based on its remaining lifetime. For equipment with a 13-year lifetime, the residual value is 0. When calculating the residual value, the investment cost is always the cost after incentives.

Table 18 and Table 19 show the lowest LCC options for gas and electric water heaters, respectively, in new construction homes. Appendix G provides plots of the LCCs in all cases. Entries with yellow shading indicate there is no other option with a LCC within 10% of the lowest LCC option, green shading indicates that there is one option with a LCC within 10% of the lowest LCC option, and blue shading indicates there are two options within 10%. Given the variability in installation costs, utility rates, maintenance costs, and capital costs, it is difficult to determine if an option will truly be cost effective in a specific installation if the LCC of two options are within 10% of one another. For specific cases, it is best to consult the plots as opposed to the tables to see how close other options are to the lowest cost option, as several options have similar LCCs.

Given that local incentive levels can vary significantly across a climate zone, analysis of what the net (federal and local combined) incentive level would need to be to make a technology cost effective is provided in the breakeven cost section below.

Table 18. Lowest LCC Gas Water Heating Option for New Construction Homes With No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Seattle	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Atlanta	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Los Angeles	Tankless	Tankless	Tankless	Tankless	Tankless	Gas Storage
Houston	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Phoenix	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

Table 19. Lowest LCC Electric Water Heating Option for New Construction Homes With No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	HPWH	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%.

For a new construction home with no incentives and gas water heating, a tankless water heater was often the most cost effective option (see Table 18). However, in most cases, a typical gas storage water heater was within 10% of being cost effective. Tankless water heaters were the most cost effective options in locations with high gas prices, such as Atlanta and Phoenix. The fact that a tankless water heater has low tank losses also led to it being cost effective in unconditioned spaces in colder climates and in conditioned spaces in warmer climates. In some high-use cases, a condensing water heater also was within 10% of being the most cost-effective option. Although condensing water heaters use slightly less energy than tankless water heaters in some high-use cases, the higher installed cost for a condensing water heater relative to a tankless water heater prevents the condensing water heater from being the lowest LCC option. Solar water heaters never came close to being cost effective because of their high installed cost.

For new construction homes with no incentives and electric water heating, HPWHs often have lower LCCs than electric storage water heaters (see Table 19). They generally do better with higher use because savings may be greater, but in many cases work out even at low use depending on local electricity rates. In most cases, the savings were so significant that the base case of an electric storage water heater was not within 10% of the LCC of a HPWH. In no case was a solar water heater close to being cost effective without incentives.

Current federal incentives apply only to solar water heaters. Even after federal incentives are applied, solar water heaters do not become cost effective because of their high net installed cost. Solar water heaters never come within 10% of being the lowest LCC option when only federal incentives are applied for gas and electric water heaters (see Table 20 and Table 21).

Table 20. Lowest LCC Gas Water Heating Option for New Construction Homes With Federal Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Seattle	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Atlanta	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Los Angeles	Tankless	Tankless	Tankless	Tankless	Tankless	Gas Storage
Houston	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Phoenix	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

Table 21. Lowest LCC Electric Water Heating Option for New Construction Homes With Federal Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	HPWH	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

When both federal and local incentives are taken into account, solar becomes an attractive option in Chicago, Atlanta, and Phoenix for homes with gas water heaters (see Table 22). A bold entry in these tables indicates that something has become cost effective over the base case when incentives are considered. Solar also becomes cost effective in some Los Angeles homes. However, a gas storage or tankless water heater continues to be the most cost-effective option in cases without local incentives. For electric water heaters, solar becomes cost effective in a few cases, particularly in locations with large local incentives but HPWHs continue to be the cost-effective option in most cases (see Table 23).

Table 22. Lowest LCC Gas Water Heating Option for New Construction Homes With Federal and Local Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	**Solar Gas**	**Solar Gas**	Tankless	**Solar Gas**	**Solar Gas**
Seattle	Gas Storage	Gas Storage	Gas Storage	Tankless	Tankless	Tankless
Atlanta	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**
Los Angeles	Tankless	Tankless	Tankless	Tankless	Tankless	**Solar Gas**
Houston	Tankless	Tankless	Tankless	Tankless	Tankless	Tankless
Phoenix	Tankless	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

Table 23. Lowest LCC Electric Water Heating Option for New Construction Homes With Federal and Local Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	HPWH	HPWH	HPWH	Electric Storage	**Solar Electric**	**Solar Electric**

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

Retrofit situations differ somewhat from new construction cases. For gas water heaters, gas storage is always the most cost-effective option (see Table 24). For gas storage water heaters, a significant portion of the installation cost in new construction comes from the venting, so it is much cheaper to install a gas storage water heater in a retrofit than in a new home. HPWHs generally continue to remain cost effective compared to other electric water heaters (see Table 25). In a retrofit, a HPWH has additional costs associated with space constraints because the tank is larger and because a louvered door may need to be installed to provide sufficient airflow around the water heater. These additional costs may make HPWHs less attractive in some cases, such as at low use in conditioned spaces in Phoenix. Although costs associated with various space constraints are also considered for tankless and condensing water heaters, the reduction in the net installed cost or a gas water heater in a retrofit home is significant enough that these costs only have a significant impact on the cost effectiveness of HPWHs.

Table 24. Lowest LCC Gas Water Heating Option for Retrofit Homes With No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Seattle	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Atlanta	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Los Angeles	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Houston	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Phoenix	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Table 25. Lowest LCC Electric Water Heating Option for Retrofit Homes With No Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	Electric Storage	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

As in the case of new construction, federal-only incentives do not change which technology has the lowest LCC, because they apply only to solar water heaters (see Table 26 and Table 27).

Table 26. Lowest LCC Gas Water Heating Option for Retrofit Homes with Federal Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Seattle	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Atlanta	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Los Angeles	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Houston	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Phoenix	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Table 27. Lowest LCC Electric Water Heating Option for Retrofit Homes with Federal Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	Electric Storage	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

When federal and local incentives are considered, solar water heaters begin to look more attractive in retrofits. For gas water heaters, solar becomes cost effective for all cases in Atlanta, most cases in Phoenix, and one case Chicago. It also comes within 10% of being cost effective for some cases in Los Angeles and most in Chicago (see Table 28). For electric water heaters, solar becomes cost effective in some situations in Chicago and Phoenix (see Table 29). However, HPWHs are usually the most cost-effective option.

Table 28. Lowest LCC Gas Water Heating Option for Retrofit Homes With Federal and Local Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	**Solar Gas**
Seattle	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Atlanta	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**
Los Angeles	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Houston	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Phoenix	Gas Storage	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

Table 29. Lowest LCC Electric Water Heating Option for Retrofit Homes With Federal and Local Incentives

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	**Solar Electric**	**Solar Electric**	**Solar Electric**
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	**Solar Electric**	HPWH	HPWH	**Solar Electric**	**Solar Electric**	**Solar Electric**

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

5.5 Breakeven Costs

Breakeven cost is how much each water heating system would need to cost (capital cost and installation costs) for it to have the same LCC as the base case of either gas or electric storage water heaters. The breakeven cost can be expressed (Equation 9) as:

$$Cost_{breakeven} = \frac{Cost_{base}+(MC_{base}-MC_{WH})+(OC_{base}-OC_{WH})}{1-\left(\frac{n-y}{n}\right)SPV_n} \quad (9)$$

where:

$Cost_{base}$	=	the base case capital cost,
MC_{base}	=	the base case maintenance cost,
MC_{WH}	=	the water heater maintenance cost,
OC_{base}	=	the base case operating cost,
OC_{WH}	=	the water heater operating cost,
N	=	the study length (13 years),
y	=	the expected water heater lifetime, and
SPV_n	=	the single present value in year N.

Breakeven cost is useful for several reasons:

- Installation costs can greatly vary from house to house (for example, a tankless water heater may need a larger gas line or a HPWH may need a louvered door).
- For homeowners, breakeven cost is useful as guidance for whether to invest in a more efficient water heating option. A homeowner who can purchase the more efficient option for less than the breakeven cost is making a cost-saving investment.
- Breakeven costs can also be used by utilities and policy makers to gauge how large incentives would need to be to make a particular technology cost effective.
- Manufacturers can use breakeven costs to determine how much the cost of a technology would need to decrease (through economics of scale, lower cost materials, new designs, or other methods) before their products would be cost neutral with the current base case.

The breakeven costs for new construction homes in each case are given in Table 30 through Table 32. Shading is used to indicate how far the current net installed cost would need to drop for each measure to become cost effective in a given scenario. The cost-saving potential of HPWHs and tankless water heaters is apparent from these charts. Condensing water heaters would usually need a cost reduction of 10%–30% (average 18%) to become cost effective. The large cost reduction necessary for solar water heaters is also apparent, as cost reductions of > 50% are almost always necessary. This also helps illustrate that current federal incentive levels for solar water heaters (set at 30% of the installed cost) are not large enough to make this technology cost effective in most situations.

Table 30. Breakeven Cost for New Construction, Low-Use Homes

Climate	Installation Location	Tankless	Condensing	Solar Gas	HPWH	Solar Electric
Chicago	Conditioned	$1,829	$1,689	$2,781	$1,780	$2,924
Seattle	Conditioned	$1,678	$1,747	$2,673	$1,406	$2,135
Atlanta	Conditioned	$2,175	$1,872	$3,354	$1,707	$2,802
Los Angeles	Conditioned	$1,989	$1,588	$2,522	$2,054	$4,272
Houston	Conditioned	$2,256	$1,664	$2,342	$2,038	$3,042
Phoenix	Conditioned	$2,414	$1,809	$2,620	$1,485	$2,471
Chicago	Unconditioned	$2,075	$1,783	$3,025	$1,562	$3,098
Seattle	Unconditioned	$2,112	$1,831	$3,123	$1,571	$2,259
Atlanta	Unconditioned	$2,385	$1,928	$3,551	$1,660	$2,880
Los Angeles	Unconditioned	$1,871	$1,586	$2,802	$2,122	$4,388
Houston	Unconditioned	$1,940	$1,653	$2,520	$1,759	$3,144
Phoenix	Unconditioned	$2,208	$1,854	$2,709	$1,247	$2,479

Red indicates a technology is cost effective at current installed costs, yellow denotes a 10% cost reduction would make a technology cost effective, green denotes a reduction of 10%–30% is required, blue denotes a reduction of 30%–50% is required, and purple denotes a reduction of > 50% is required

Table 31. Breakeven Cost for New Construction, Medium-Use Homes

Climate	Installation Location	Tankless	Condensing	Solar Gas	HPWH	Solar Electric
Chicago	Conditioned	$1,806	$1,806	$3,113	$2,301	$3,386
Seattle	Conditioned	$1,661	$1,851	$2,877	$1,799	$2,396
Atlanta	Conditioned	$2,136	$1,990	$3,923	$2,212	$3,340
Los Angeles	Conditioned	$1,960	$1,684	$3,073	$2,728	$5,089
Houston	Conditioned	$2,218	$1,766	$2,880	$2,728	$3,732
Phoenix	Conditioned	$2,359	$1,904	$3,159	$1,883	$3,043
Chicago	Unconditioned	$2,062	$1,898	$3,334	$1,947	$3,533
Seattle	Unconditioned	$2,081	$1,946	$3,300	$1,979	$2,520
Atlanta	Unconditioned	$2,342	$2,060	$4,106	$2,110	$3,386
Los Angeles	Unconditioned	$1,845	$1,678	$3,263	$2,780	$5,182
Houston	Unconditioned	$1,896	$1,729	$2,998	$2,302	$3,828
Phoenix	Unconditioned	$2,127	$1,909	$3,187	$1,555	$3,060

Red indicates a technology is cost effective at current installed costs, yellow denotes a 10% cost reduction would make a technology cost effective, green denotes a reduction of 10%–30% is required, blue denotes a reduction of 30%–50% is required, and purple denotes a reduction of > 50% is required

Table 32. Breakeven Cost for New Construction, High-Use Homes

Climate	Installation Location	Tankless	Condensing	Solar Gas	HPWH	Solar Electric
Chicago	Conditioned	$1,791	$1,931	$3,350	$2,558	$3,583
Seattle	Conditioned	$1,642	$1,980	$3,048	$1,955	$2,557
Atlanta	Conditioned	$2,106	$2,133	$4,352	$2,512	$3,605
Los Angeles	Conditioned	$1,929	$1,785	$3,425	$3,090	$5,532
Houston	Conditioned	$2,180	$1,875	$3,237	$3,141	$4,118
Phoenix	Conditioned	$2,316	$2,014	$3,657	$2,212	$3,496
Chicago	Unconditioned	$2,039	$2,028	$3,560	$2,105	$3,717
Seattle	Unconditioned	$2,050	$2,079	$3,450	$2,133	$2,665
Atlanta	Unconditioned	$2,296	$2,201	$4,488	$2,341	$3,652
Los Angeles	Unconditioned	$1,816	$1,774	$3,590	$3,083	$5,608
Houston	Unconditioned	$1,863	$1,821	$3,355	$2,629	$4,208
Phoenix	Unconditioned	$2,064	$1,989	$3,633	$1,791	$3,515

Red indicates a technology is cost effective at current installed costs, yellow denotes a 10% cost reduction would make a technology cost effective, green denotes a reduction of 10%–30% is required, blue denotes a reduction of 30%–50% is required, and purple denotes a reduction of > 50% is required

Breakeven costs for retrofit homes are provided in Table 33 to Table 35. Once again, HPWHs are cost effective in most cases; in one case a cost reduction > 10% of the level assumed here is required. However, for any gas water heating technology to be able to compete with a typical gas storage water heater, the installed costs would usually have to decrease by at least 30%. For tankless water heaters, the average drop across all situations would have to be 36% to make this technology cost effective. For condensing water heaters, that number would have to be 42%. Solar once again would require a drop in net installed costs greater than current federal incentive levels to be cost effective. Solar water heating with electric backup fares slightly better than solar water heating with gas backup because a two-tank system has higher installed costs and lower energy savings. On average, costs would need to drop 47% for a solar water heater electric backup to be cost effective; an average drop of 65% would be required to make a solar water heater with gas backup cost effective.

Table 33. Breakeven Cost for Retrofit, Low-Use Homes

Climate	Installation Location	Tankless	Condensing	Solar Gas	HPWH	Solar Electric
Chicago	Conditioned	$1,350	$1,328	$2,181	$1,911	$3,142
Seattle	Conditioned	$1,200	$1,386	$2,073	$1,537	$2,352
Atlanta	Conditioned	$1,697	$1,511	$2,754	$1,838	$3,019
Los Angeles	Conditioned	$1,510	$1,227	$1,923	$2,185	$4,489
Houston	Conditioned	$1,778	$1,303	$1,743	$2,169	$3,260
Phoenix	Conditioned	$1,935	$1,448	$2,021	$1,616	$2,689
Chicago	Unconditioned	$1,597	$1,422	$2,425	$1,693	$3,315
Seattle	Unconditioned	$1,633	$1,470	$2,524	$1,702	$2,476
Atlanta	Unconditioned	$1,907	$1,567	$2,952	$1,791	$3,098
Los Angeles	Unconditioned	$1,393	$1,225	$2,203	$2,253	$4,605
Houston	Unconditioned	$1,461	$1,292	$1,921	$1,890	$3,362
Phoenix	Unconditioned	$1,730	$1,493	$2,110	$1,378	$2,696

Red indicates a technology is cost effective at current installed costs, yellow denotes a 10% cost reduction would make a technology cost effective, green denotes a reduction of 10%–30% is required, blue denotes a reduction of 30%–50% is required, and purple denotes a reduction of > 50% is required

Table 34. Breakeven Cost for Retrofit, Medium Use Homes

Climate	Installation Location	Tankless	Condensing	Solar Gas	HPWH	Solar Electric
Chicago	Conditioned	$1,328	$1,445	$2,514	$2,432	$3,603
Seattle	Conditioned	$1,183	$1,490	$2,278	$1,930	$2,613
Atlanta	Conditioned	$1,658	$1,629	$3,324	$2,343	$3,558
Los Angeles	Conditioned	$1,481	$1,323	$2,474	$2,859	$5,306
Houston	Conditioned	$1,739	$1,405	$2,281	$2,859	$3,949
Phoenix	Conditioned	$1,881	$1,543	$2,560	$2,014	$3,260
Chicago	Unconditioned	$1,583	$1,537	$2,735	$2,078	$3,750
Seattle	Unconditioned	$1,603	$1,585	$2,700	$2,110	$2,738
Atlanta	Unconditioned	$1,863	$1,699	$3,507	$2,241	$3,604
Los Angeles	Unconditioned	$1,366	$1,317	$2,664	$2,911	$5,399
Houston	Unconditioned	$1,418	$1,368	$2,399	$2,433	$4,045
Phoenix	Unconditioned	$1,649	$1,548	$2,588	$1,686	$3,277

Red indicates a technology is cost effective at current installed costs, yellow denotes a 10% cost reduction would make a technology cost effective, green denotes a reduction of 10%–30% is required, blue denotes a reduction of 30%–50% is required, and purple denotes a reduction of > 50% is required

Table 35. Breakeven Cost for Retrofit, High Use Homes

Climate	Installation Location	Tankless	Condensing	Solar Gas	HPWH	Solar Electric
Chicago	Conditioned	$1,312	$1,570	$2,751	$2,689	$3,800
Seattle	Conditioned	$1,164	$1,619	$2,449	$2,086	$2,774
Atlanta	Conditioned	$1,627	$1,772	$3,753	$2,643	$3,823
Los Angeles	Conditioned	$1,450	$1,424	$2,826	$3,221	$5,750
Houston	Conditioned	$1,702	$1,514	$2,638	$3,272	$4,336
Phoenix	Conditioned	$1,838	$1,653	$3,058	$2,343	$3,713
Chicago	Unconditioned	$1,561	$1,667	$2,961	$2,236	$3,934
Seattle	Unconditioned	$1,571	$1,718	$2,851	$2,264	$2,883
Atlanta	Unconditioned	$1,817	$1,840	$3,889	$2,472	$3,869
Los Angeles	Unconditioned	$1,338	$1,413	$2,991	$3,214	$5,826
Houston	Unconditioned	$1,384	$1,460	$2,755	$2,760	$4,426
Phoenix	Unconditioned	$1,586	$1,628	$3,034	$1,922	$3,732

Red indicates a technology is cost effective at current installed costs, yellow denotes a 10% cost reduction would make a technology cost effective, green denotes a reduction of 10%–30% is required, blue denotes a reduction of 30%–50% is required, and purple denotes a reduction of > 50% is required

6 Conclusions

Simulations were performed comparing advanced electric and gas water heaters to their respective base cases of electric resistance and natural draft gas storage water heaters in a variety of climates, in conditioned and unconditioned spaces, and with several realistic draw profiles. These simulations show that solar water heaters use the least amount of source energy of any gas water heating option in almost every scenario, although tankless water heaters use less energy in low-use homes in cooling-dominated climates. Solar water heaters have the potential to save an average of 6.2 MMBtu/yr of source energy per household across all households; the highest potential savings were in high-use cases in cold and temperate locations where the water heating demand is greater. Tankless and condensing water heaters saved an average of 3.6 MMBtu/yr per household. However, tankless water heaters outperformed condensing water heaters in situations where the tank losses from the condensing water heaters were detrimental, such as in conditioned spaces in homes in warm climates and in low-use cases in unconditioned spaces.

For electric water heaters, HPWHs were able to provide comparable or better energy savings than solar water heaters under many scenarios examined here However, the HPWH modeled here is also based on one manufacturer's model and does not represent the entire range of performance seen in all HPWHs on the market today. On average across all climates, HPWHs were shown to have the potential to save 15.2 MMBtu/yr per household. The HPWH provides higher savings in all locations at higher use. For the buildings modeled here, locating a HPWH in conditioned space achieves higher savings in all locations except Seattle and Los Angeles. Solar water heaters with electric backup were able to save an average of 17.3 MMBtu/yr per household; the highest savings were in moderate climates under medium and high use. Solar water heaters slightly outperformed HPWHs in most cases, with notable exceptions in some high-use cases in conditioned spaces and in most cases in Seattle with its poor solar resource. However, larger collector areas would change this result.

LCC and breakeven cost calculations were also performed for all these technologies to determine their cost effectiveness in new construction and retrofit scenarios. HPWHs were often the most cost-effective electric water heating option with average 13-year LCC savings of about $700 in new construction homes and $625 in retrofit homes. The highest LCC cost savings occurred in medium- and high-use homes in Houston and Los Angeles. For gas water heaters, tankless water heaters in new construction homes were cost effective in most cases. However, the LCC cost savings in all locations were modest with an average savings of about $225 and a maximum savings of about $425. These savings are < 10% of the LCC of the tankless water heater. For gas water heaters in retrofit scenarios, no advanced water heating technology was cost effective, as the advanced technologies are more expensive to install in retrofit scenarios. Gas storage water heaters are also cheaper to install in retrofit scenarios because existing venting can be used, further increasing the gap between typical gas water heaters and advanced gas water heating technologies.

The breakeven cost calculations performed here were used to demonstrate how much current net installed costs for advanced water heating technologies would need to drop through a combination of incentives, lower equipment costs, and lower installation costs for these technologies to be cost effective. Although tankless water heaters were largely cost effective in new construction homes, a reduction of the net installed cost of 30%–50% would be required in most retrofit homes for this technology to be cost effective. Condensing water heaters would need a reduction of 10%–30% to compete with typical gas storage water heaters in new construction homes and 30%–50% in retrofit homes. Solar water heaters with both gas and electric backup would need a cost reduction of > 50% to compete in most cases.

Incentives mostly applied to solar water heating. In cases where both federal and local incentives are considered, solar water heaters can be cost effective in about one third of the situations considered here compared to gas water heaters and less than one sixth of the situations considered here compared to electric water heaters. This shows that although current incentive levels make the economics of solar water heating more favorable, they do not make these technologies cost-effective replacements for typical gas and electric storage water heaters.

References

1. **Energy Information Administration (EIA).** *Residential Energy Consumption Survey.* Washington, DC : US Department of Energy, 2005.
2. **US Department of Energy.** *Energy Star Water Heater Market Profile.* Washington, DC : US Department of Energy, 2010.
3. —. *10 CFR Part 430 Energy Conservation Program for Consumer Products: Test Procedure for Water Heaters.* s.l. : Federal Register Vol. 63, No. 90, 1998.
4. **Energy Information Administration (EIA).** *Residential Energy Consumption Survey (RECS).* Washington, DC : US Department of Energy, 2009.
5. **Environmental Protection Agency Office of Air and Radiation.** *National Awareness of ENERGY STAR for 2008: Analysis of 2008 CEE Household Surve.* 2009.
6. **US Department of Energy.** *Water Heater Market Profile.* Washington, DC : US Department of Energy, 2009.
7. —. *Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters; Final Rule.* s.l. : Federal Register, 2010.
8. *Condensing Natural Gas Water Heaters.* **Pescatore, P, Roth, K and Brodrick, J.** February 2004, ASHRAE, pp. 51-52.
9. **US Department of Energy (DOE).** *Residential Water Heater Final Rule Making Technical Support Document.* Washington, DC : Departmet of Energy, 2001.
10. **California Energy Commission & California Public Utilities Commission.** California Solar Initiative - Thermal Program. *GoSolarCalifornia.* [Online] [Cited: April 26, 2012.] http://www.gosolarcalifornia.org/solarwater/index.php.
11. **Pacific Gas & Electric (PG&E) Applied Technology Services.** *Laboratory Testing of Residential Gas Water Heaters.* San Ramon, CA : PG&E, 2008.
12. **Hendron, R. and Engelbrecht, C.** *Building America House Simulation Protocol.* Golden, CO : National Renewable Energy Laboratory, 2010.
13. **Bohac, D., et al., et al.** *Actual Savings and Performance of Natural Gas Tankless Water Heaters.* Minneapolis : Minnesota Center for Energy and Environment, 2010.
14. **Pescatore, P.** *Development of a Market Optimized Condensing Gas Water Heater.* s.l. : TIAX, 2006.
15. **Dubay, K., Ayee, G. and Gereffi, G.** *Manufacturing Climate Solutions: Carbon-Reducing Technologies and U.S. Jobs-Chapter 6: Electric Heat Pump Water Heaters.* Durham : Manufacturing Climate Solutions, 2009.
16. **Solar Energy Industries Association (SEIA) and Greentech Media Research (GTM).** *U.S. Solar Market Insight: 2nd Quarter 2010 - Executive Summary.* Washington, DC : SEIA, 2010.
17. *Field and Laboratory Testing of Gas Tenkless Water Heater Performance.* **Hoeschele, M., Springer, D.** 2, s.l. : ASHRAE Transactions, 2008, Vol. 114.
18. *Economics of residential gas furnaces and water heaters in US new construction market.* **Lekov, A., et al., et al.** 2009, Energy Efficiency Online Publication.
19. **Hiller, C.** *Commentary on the Energy Star Water Heating Program.* Washington, DC : Energy Star, 2007.
20. *A Review of Heat Pump Water Heating Systems.* **Hepbasli, A. and Kalinci, Y.** 2009, Renewable and Sustainable Energy Reviews, pp. 1211-1229.

21. **Hashimoto, K.** *Technology and Market Development of CO2 Heat Pump Water Heaters (ECO CUTE) in Japan.* s.l. : IEA Heat Pump Centre Newsletter, 2006.
22. **Hudon, K. Merrigan, T. Burch, J. Maguire, J.** *Low-Cost Solar Water Heating Research and Development Roadmap.* Golden, CO : National Renewable Energy Laboratory, 2012. NREL/TP-5500-54739.
23. **US Department of Energy.** *Energy Star Qualified Water Heaters-Partner Guide.* s.l. : US Department of Energy, 2009. pp. 1-13.
24. **Goswami, Y., Kreith, F. and Kreider, J.** *Principles of Solar Engineering.* New York : Taylor & Francis Group, 2000.
25. **Schollenberger, F.** Passive Solar Collector Freeze Characteristics. *Master's Thesis.* Boulder, CO : University of Colorado, 2011.
26. **Siegenthaler, J.** Active Solar Heating: New Opportunities for Hydronics Pros (Webinar). May 2008.
27. **Weiss, W., Bergmann, I. and Faninger, G.** *Solar Heat Worldwide: Markets and Contribution to the Energy Supply 2006.* Gleisdorf : IEA, 2008.
28. **Solar Ratings and Certification Corporation (SRCC).** *Methodology for Determining the Thermal Performance Rating for Solar Collectors.* Cocoa : SRCC, 1994.
29. *TRNSYS 17: A TRaNsient System Simulation Program, User Manual.* **Klein, S et al.** Madison, WI : Solar Energy Laboratory, University of Wisconsin, 2010.
30. **Thermal Energy System Specialists (TESS).** *Type 534: Vertical Cylinder Water Heater Documentation.* Madison, WI : TESS, 2004.
31. —. *Type 539: Solar Collector with Capacitance Effects and Controls to Maintain a Desired Outlet Temperature.* Madison, WI : TESS, 2010.
32. **Grant, P.** Evaluation of the Performance of Gas Tankless Water Heaters. *Master's Thesis.* Boulder, CO : University of Colorado Boulder, 2010.
33. **Maguire, J.** A Parametric Analysis of Residential Water Heaters. *Master's Thesis.* Boulder, CO : University of Colorado Boulder, 2012.
34. *Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings.* **Hendron, R. and Burch, J.** Long Beach : National Renewable Energy Lab, 2007. Energy Sustainability. pp. 1-8.
35. *Using Ratings Data to Derive Simulation-Model Inputs for Storage-Tank Water Heaters.* **Burch, J. and Erikson, P.** Portland, Oregon : s.n., 2004. Poceedings of the 29th Passive Solar Conference. pp. 393-398.
36. **Thermal Energy System Specialists (TESS).** *Documentation for Heat Pump Water Heater Type 938.* Madison, WI : TESS, 2010.
37. **Sparn, B. Hudon, K. Christensen, D.** *Laboratory Performance Evaluation of Residential Integrated Heat Pump Water Heaters.* Golden, CO : National Renewable Energy Laboratory (NREL), 2011.
38. **Thermal Energy System Specialists (TESS).** TRNSYS-TESS Libraries. *TESS Library General Descriptions.* [Online] 2011. [Cited: July 20, 2011.] http://www.trnsys.com/tess-libraries/TESSLibs17_General_Descriptions.pdf.
39. **Ramlow, B. and Nusz, B.** *Solar Water Heating: A Comprehensive Guide to Solar Water Heating and Space Heating Systems.* Gabriola Island : New Society Publishers, 2006.
40. **Hendron, R., Hancock, E. and Reeves, P.** *Building America Field Test and Analysis Report: CORE H1 and H2 Houses - Carbondale, CO.* Golden, CO : National Renewable Energy Laboratory, 2005.

41. **Solar Ratings and Certification Corporation (SRCC).** *OG 300: Operating Guidelines and Minimum Standards for Certifying Solar Water Heating Systems.* Cocoa, FL : SRCC, 2010.
42. **Casey, R.** Performance Modeling of a Building Integrated Photovoltaic/Thermal Air Collector. *Master's Thesis.* Boulder, CO : University of Colorado Boulder, 2009.
43. **Interational Code Council (ICC).** *International Energy Conservation Code.* Falls Church, VA : ICC, 2009.
44. **Pacific Northwest National Laboratory and Oak Ridge National Laboratory.** *Building America Best Practice Series-Guid to Determining Climate Regions by County.* s.l. : US Department of Energy, 2007.
45. **Oak Ridge National Laboratory (ORNL).** *1988.* Oak Ridge, Tennessee : ORNL, Building Foundation Design Handbook.
46. **Winklemann, F.** *Underground Surfaces: How to get Better Underground Surface Heat Transfer Calculations in DOE2.1E.* Berkeley, CA : LBNL, 2003.
47. **Mayer, P. and DeOreo, W.** *Residential End Uses of Water.* Boulder CO : Aquacraft, Inc, 1999.
48. *Towards Development of an Algorithm for Mains Water Temperature.* **Burch, J. and Christensen, C.** Cleveland, OH : ASES Annual Conference, 2007.
49. **Solar Ratings and Certification Corporation (SRCC).** Solar Facts - System Ratings. *SRCC.* [Online] 2011. [Cited: October 31, 2011.] http://www.solar-rating.org/facts/system_ratings.html.
50. *Effects of Tilt and Azimuth on Annual Incident Solar Radiation for United States Locations.* **Christensen, C. and Barker, G.** Washington, DC : Solar Forum 2001, 2001.
51. *Tankless Water Heaters: Do They Really Save Energy?* **Schoenbauer, B., Bohac, D., Hewett, M.** Pacific Grove, CA : 2012 ACEEE Summer Study on Energy Efficiency in Buildings, 2012.
52. **Pexsupply.com.** AO Smith Vertex Water Heater: 76000 Btu/h. *Pexsupply.com.* [Online] [Cited: April 24, 2012.] http://www.pexsupply.com/AO-Smith-GPHE-50-CUSTOM-50-Gallon-76000-BTU-Vertex-Power-Vent-Residential-Gas-Water-Heater-Custom-Order.
53. **Wayfair.com.** A.O. Smith Water Heater Residential High Efficiency Power Vent Nat Gas 50 Gal Vertex 76,000 BTU. *Wayfair.* [Online] [Cited: April 24, 2012.] http://www.wayfair.com/A.O.-Smith-Water-Heater-Residential-High-Efficiency-Power-Vent-Nat-Gas-50-Gal-Vertex-76-000-BTU-GPHE-50-QOS1187.html?refid=FR49-QOS1187.
54. **HomePerfect.com.** AO Smith GPHE-50 50 Gallon Vertex Power-Vent Residential Gas Water Heater - 76,000 BTU. *HomePerfect.com.* [Online] [Cited: April 24, 2012.] http://www.homeperfect.com/ao-smith-gphe-50-50-gallon-vertex-power-vent-residential-gas-water-heater-76-000-btu.html?utm_source=googlebase&utm_medium=comparisonshopping.
55. **Reed Construction Data.** *RSMeans Cost Books: Residential New Construction.* s.l. : Robert S Means Company, 2012.
56. **Interstate Renewable Energy Council (IREC).** US National Database of State Incentives for Renewables and Efficiency (DSIRE). *DSIRE.* [Online] Intersate Rnewable Energy Council, 2011. [Cited: November 10, 2011.] http://www.dsireusa.org/.
57. **National Renewable Energy Laboratory.** *Solar Water Heating.* Washingto, DC : US DOE Office of Energy Efficiency and Renewable Energy Clearinghouse, 1996.
58. **Cassard, H., Denholm, P. and Ong, S.** *Break-even Cost for Residential Solar Water Heating in the United States: Key Drivers and Sensitivities.* Golden, CO : National Renewable Energy Laboratory (NREL), 2011.

59. **Energy Information Administration (EIA).** *Electric sales, revenue, and average price.* Washington, DC : EIA, 2010.
60. **Fuller, S., Peterson, S.** *Life-Cycle Costing Manual for the Federal Energy Management Program.* Gaithersburg, MD : National Institute of Standards and Technology (NIST), 1995.
61. **Rushing, A., Kneifel, J., and Lippiatt, B.** *Annual Supplement to NIST Handbook 135 and NBS Special Publication 709.* Washington, DC : US Department of Commerce, 2010.
62. **Butti, K. and Perlin, J.** *A Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto : Van Nostrand Reinhold Company, 1980.
63. **National Renewable Energy Laboratory (NREL) Geographic Information Systems.** Solar Radiation Map. *NREL Geographic Information Systems.* [Online] NREL, May 20, 2011. [Cited: October 25, 2011.] http://www.nrel.gov/gis/solar.html.

Appendix A Water Heater Model Parameters

Table 36. Model Parameters for Gas Water Heaters

Model Parameter	Units	Gas Storage	Tankless	Condensing Storage
Storage Volume	*gallons*	47.6	NA	47.6
Overall Heat Loss Coefficient (UA)	*Btu/h·°F*	8.40	4.76	6.01
Input Power	*kBtu/h*	50	10-150	85
Combustion Efficiency	–	0.771	0.802	Varies, see Figure 12
Pilot Light Power	*kBtu/h*	0.45	NA	NA
Pilot Light Combustion Efficiency	–	0.771	NA	NA
Capacitance	*kJ/K*	NA	8.36	NA
Idle Power	*W*	NA	10	16
Running Power	*W*	NA	65	37
Freeze Protection Power	*W*	NA	100	NA

Table 37. Model Parameters for Electric Water Heaters

Model Parameter	Units	Electric Resistance	HPWH
Storage Volume	*gallons*	45.5	45.6
Overall Heat Loss Coefficient (UA)	*Btu/h·°F*	3.29	3.97
Element Power	*kW*	4.5	4.5
Element Conversion Efficiency	–	1	1
Rated Compressor Power	*kW*	NA	0.7
Idle Power	*W*	NA	3

Table 38. Solar Water Heater Collector Parameters

Model Parameter	Units	All Solar Water Heaters
Collector Area	ft^2	32
Number of Collectors	–	2
Working Fluid	–	50% glycol, 50% water
Intercept Efficiency (a0)	–	0.691
1st Order Efficiency Coefficient (a1)	$kJ/h \cdot m^2 \cdot K$	12.128
2nd Order Efficiency Coefficient (a2)	$kJ/h \cdot m^2 \cdot K^2$	0.0708
1st Order IAM Coefficient	–	–0.194
2nd Order IAM Coefficient	–	0.006
Collector Capacitance	kJ/kg	17.7
Collector Piping Net Length	ft	50
Piping Insulation Thickness	in	0.75
Piping Insulation R-value	$ft^2 \cdot h \cdot °F/Btu$	3.97
Pump Power	W	29.8
Idle Power	W	2

Table 39. Solar Storage Tank Parameters

Model Parameter	Units	Solar With Gas Backup	Solar With Electric Backup
Solar Tank Storage Volume	*gallons*	72.1	72.1
Solar Tank Overall Heat Loss Coefficient (UA)	*Btu/h·°F*	2.75	2.75
Solar Tank Input Power	*kW*	0	4.5
Solar Tank Conversion Efficiency	–	NA	1
Backup Tank Storage Volume	*gallons*	47.6	NA
Backup Tank Overall Heat Loss Coefficient (UA)	*Btu/h·°F*	8.40	NA
Backup Tank Input Power	*kBtu/h*	50	NA
Backup Tank Conversion Efficiency	–	0.771	NA
Backup Tank Pilot Light Power	*kBtu/h*	0.45	NA
Backup Tank Pilot Light Combustion Efficiency	–	0.771	NA

Appendix B Impact of Modeling a Pilot Light on Gas Water Heater Energy Consumption

Some modeling tools explicitly model a pilot light. Others do not, assuming that all the energy consumed by the pilot light goes to offsetting standby losses. To determine the impact of modeling the pilot light on the predicted annual energy consumption of a gas water heater (either used by itself or as a backup for a solar water heater), simulations were performed both with and without a standing pilot light. The pilot light modeled here consumes 450 Btu/h, a typical size for gas water heaters (9), and has the same efficiency as the conversion efficiency of the water heater (77.1% for this particular water heater; details of how this was determined are provided below). Simulations were run for all draw profiles, climates, and installation locations. The inclusion of a pilot light had minimal impact on a gas water heater's annual energy consumption in most cases, but had a significant impact on the annual energy consumption of a solar water heating system that uses a gas water heater for backup.

To determine the efficiency of the pilot light, time-series data from an EF test of a minimum efficiency 40-gallon gas water heater with a pilot light was analyzed. During the period after the last draw of the test, only the pilot light added heat to the tank and the tank temperature slowly decayed from standby losses. A TRNSYS model of this water heater was created and simulations of this standby period were run with different amounts of heat from the pilot entering the tank. The actual input from the pilot to the tank was determined by finding the input value that minimized the difference between the measured and modeled average tank temperatures. The measured and modeled average tank temperatures for the pilot light input value that provided the best fit are shown in Figure 43.

The pilot light efficiency can be calculated by using this energy input into the tank and the measured gas consumption. In this case, the calculated pilot light efficiency is 75.2%, the measured recovery efficiency of the unit is 75.5%, and the calculated combustion efficiency is 77.1%. The measured pilot light efficiency is slightly lower than the combustion efficiency of the unit; however, errors in the measurements and the fact that only one unit was analyzed makes it difficult to determine if the pilot light efficiency is generally lower than the combustion efficiency of the burner for gas storage water heaters with a standing pilot. As a result, the pilot light efficiency was assumed to be the same as the combustion efficiency for the simulations performed here.

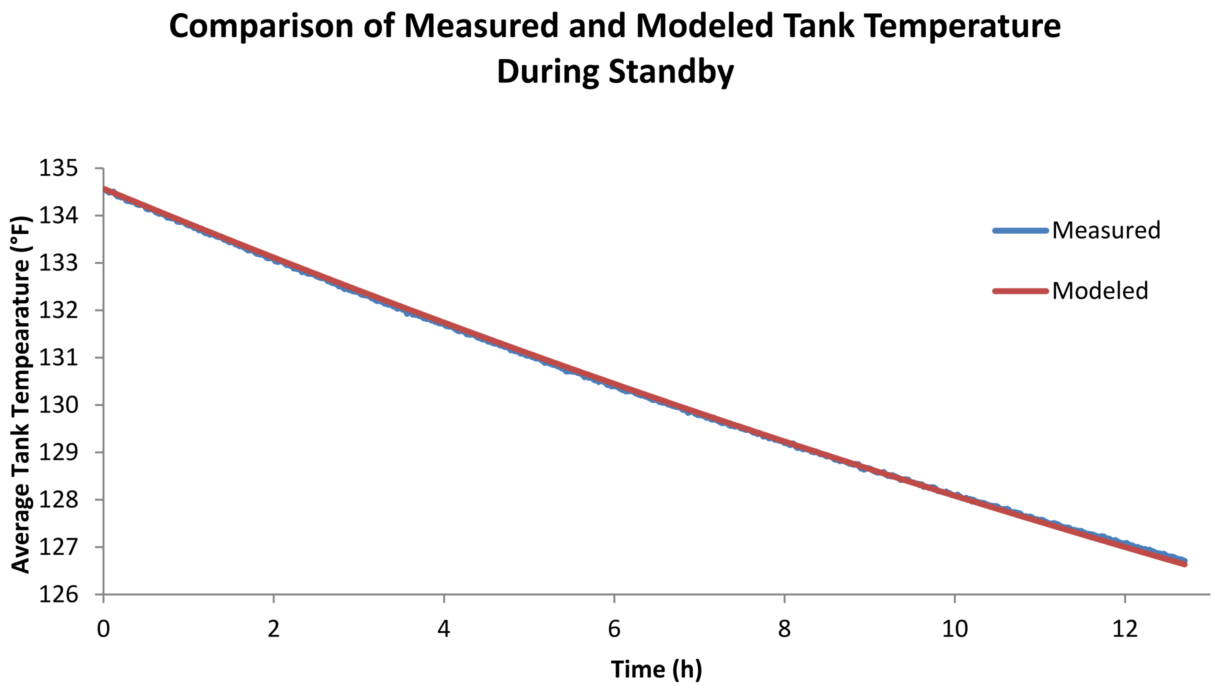

Figure 43. Average tank temperatures during the standby period of the EF test. Note that the first few hours of the test period were not analyzed, so any mixing induced by the burner from the analysis period was excluded.

With the pilot light efficiency known, simulations analyzing the impact of the pilot on the annual efficiency of a gas water heater were performed. Adding a standing pilot has two major impacts on the annual energy consumption of the water heater. Because the pilot runs continuously, consuming 450 Btu/h for the full year (8760 hours), there is a minimum energy consumption of 3,940,000 Btu/yr (39.4 therm/yr) for all gas water heaters with standing pilots. However, this energy is not wasted in a regular gas storage water heater. Three hundred forty-seven Btu/h goes into the tank from the pilot light (the product of the pilot energy consumption and the pilot light combustion efficiency). This energy addition into the tank helps offset standby losses and is not wasted. To help illustrate this, consider an energy balance on the water heater in the case where both the burner and pilot light are turned off. Using the UA value of this gas water heater and assuming the tank is isothermal at 120°F in a 70°F room, the standby losses (Equation 10) will be:

$$\dot{Q} = (UA)\Delta T \rightarrow \dot{Q} = \left(8.4\,\frac{Btu}{hr\cdot^{\circ}F}\right)(50^{\circ}F) = 420\,\frac{Btu}{hr} \qquad (10)$$

where:

$\dot{Q}$	=	the rate of heat loss from the tank to ambient air,
UA	=	the overall heat loss coefficient of the tank, and
ΔT	=	the temperature difference between the tank and ambient air.

In this case, the heat added to the tank from the pilot light is less than the standby losses and reduces the rate at which the tank cools, leading to longer periods between the burner firing to make up standby losses. The energy balance used above can also be solved for the temperature difference that can be sustained by the pilot light (Equation 11), which yields:

$$\dot{Q} = (UA)\Delta T \rightarrow 347\frac{Btu}{hr} = \left(8.4\ \frac{Btu}{hr \cdot {}^{\circ}F}\right)(\Delta T) \rightarrow \Delta T = 41.3^{\circ}F \qquad (11)$$

This means that, with no draws, the pilot light alone can keep the tank roughly 40°F warmer than the surrounding air. In cases where the temperature difference is > 40°F, the energy used by the pilot goes to making up standby losses and is useful. If the temperature difference is < 40°F, the pilot light will heat the tank above its set point temperature. In this case, some of the pilot light energy is wasted as it goes to overheating the tank. Water heaters in conditioned space always have a temperature difference > 40°F, so the pilot energy is never wasted by overheating the tank. However, for water heaters in unconditioned spaces in hot climates, the ambient temperature can be high enough to cause the pilot light to overheat the tank.

Even in cases of water heaters in conditioned spaces or water heaters in unconditioned spaces in colder climates, including a pilot light causes a slight increase in the annual gas consumption of the water heater because tank losses increase; the pilot light causes the average tank temperature during standby periods to be slightly higher than in tanks without standing pilot lights. In cases where there is a pilot light, the tank cools more slowly and it takes a much longer time (more than 24 hours) for the burner to fire to make up standby losses. This means that for several hours after a draw, the average temperature and tank losses for a gas water heater with a pilot light will be larger than for a unit without a pilot light. A draw typically forces the burner of the water heater with a pilot light to fire before the unit needs to turn on to make up standby losses, so on average the unit with a pilot light has higher standby losses and consumes slightly more energy than the unit without a pilot light. Figure 44 shows the average tank temperature and difference in standby losses over a three-day period for units with and without a pilot light.

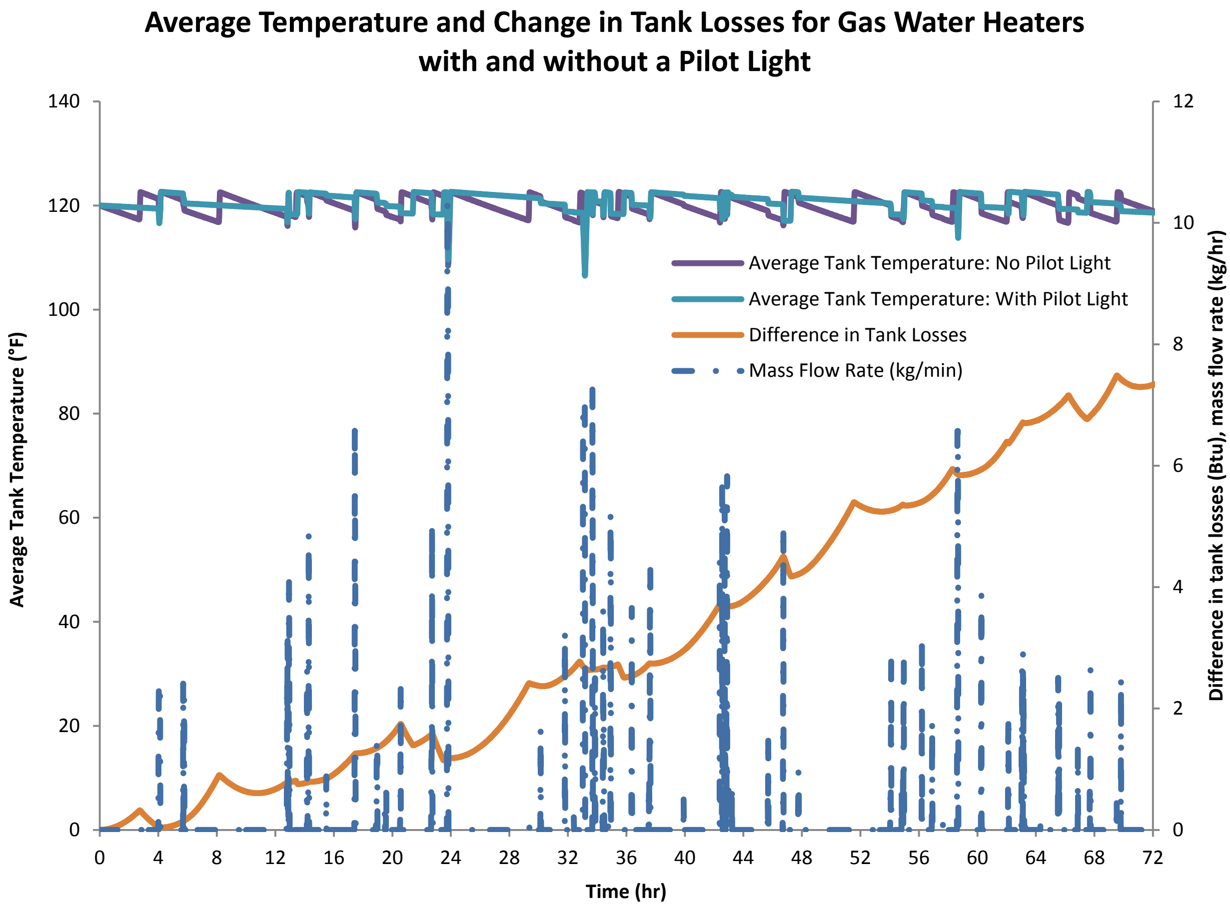

Figure 44. Average tank temperatures and differences in standby losses for units with and without pilot lights

The increase in energy consumption from including a pilot light in the gas water heater model is presented in Figure 45. Energy consumption increases in all cases, but is < 1 therm (~1% of the annual energy consumption) in most cases. The increase becomes significant only in cases where the water heater is in unconditioned space in a hot climate, because the high ambient air temperature causes the tank to overheat during summer months. These results show that modeling the pilot light has a significant impact only in cases where the ambient air temperature can cause the tank to overheat.

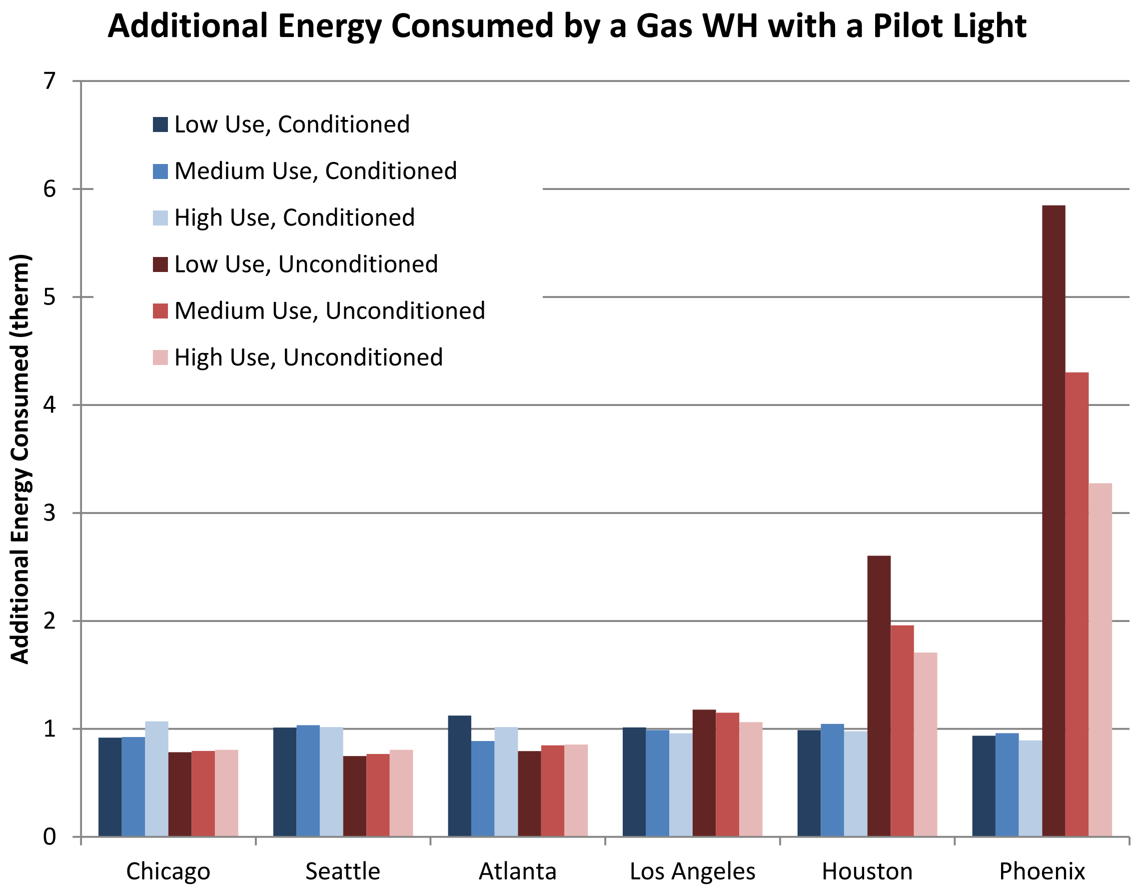

Figure 45. Increase in modeled gas water heater energy consumption from the inclusion of a pilot light

When a gas water heater with a pilot light is used as a backup for a solar water heater, the increase in energy consumption may be significantly larger (see Figure 46). In cases where a gas water heater is used as a backup for a solar water heater, hot water from the solar storage tank enters the tank during draws. If this preheated water brings the average gas tank temperature over the set point temperature (which often happens when the solar storage tank has been charged by the collector loop), the pilot light energy keeps the tank overheated for a longer period, which increases the standby losses. This leads to additional wasted energy in all cases where a gas water heater is used as a backup to a solar water heater.

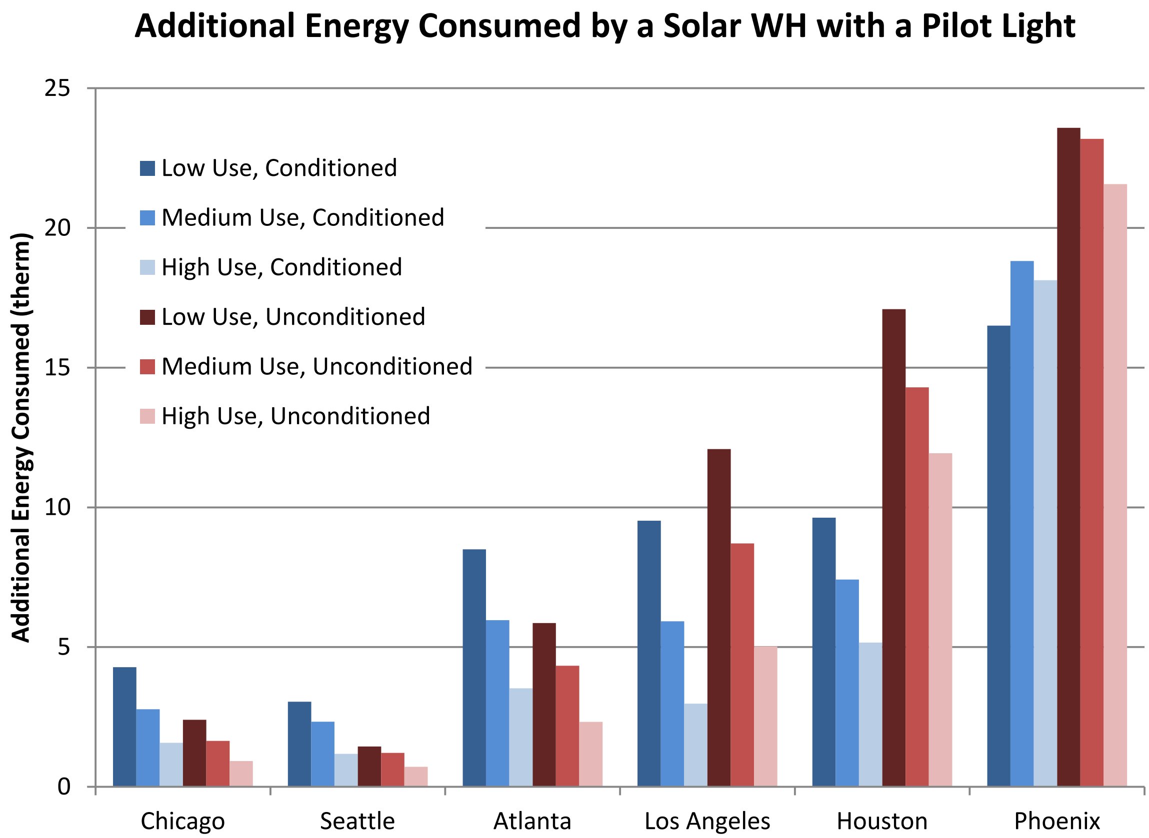

Figure 46. Increase in modeled solar water heater energy consumption from the inclusion of a pilot light

In general, more energy is wasted in low-use cases because the solar storage tank can charge more often and to higher temperatures. The wasted energy is also greater in locations with a larger solar resource, as the losses are proportional to how much preheated water the solar water heater can provide. In cold climates, the wasted energy is smaller in unconditioned spaces (relative to conditioned spaces), where the pilot light energy goes toward offsetting standby losses more often.

Figure 47 shows one situation, the low-use conditioned space case in Phoenix, which reverses the trend: the low-use case does not waste more energy than the medium-use case. In this particular case, the solar water heater is oversized for the available solar resource which means that the gas burner does not need to fire to meet the water heating load during several months. During these months, the amount of wasted energy is driven by how often the gas water heater is charged by the solar storage tank because the water in the storage tank is hotter than the setpoint temperature. The unit is charged every time there is a draw, so at lower draw volumes less energy is wasted during these months. At higher draw volumes, the collector is no longer oversized, so less pilot light energy is wasted.

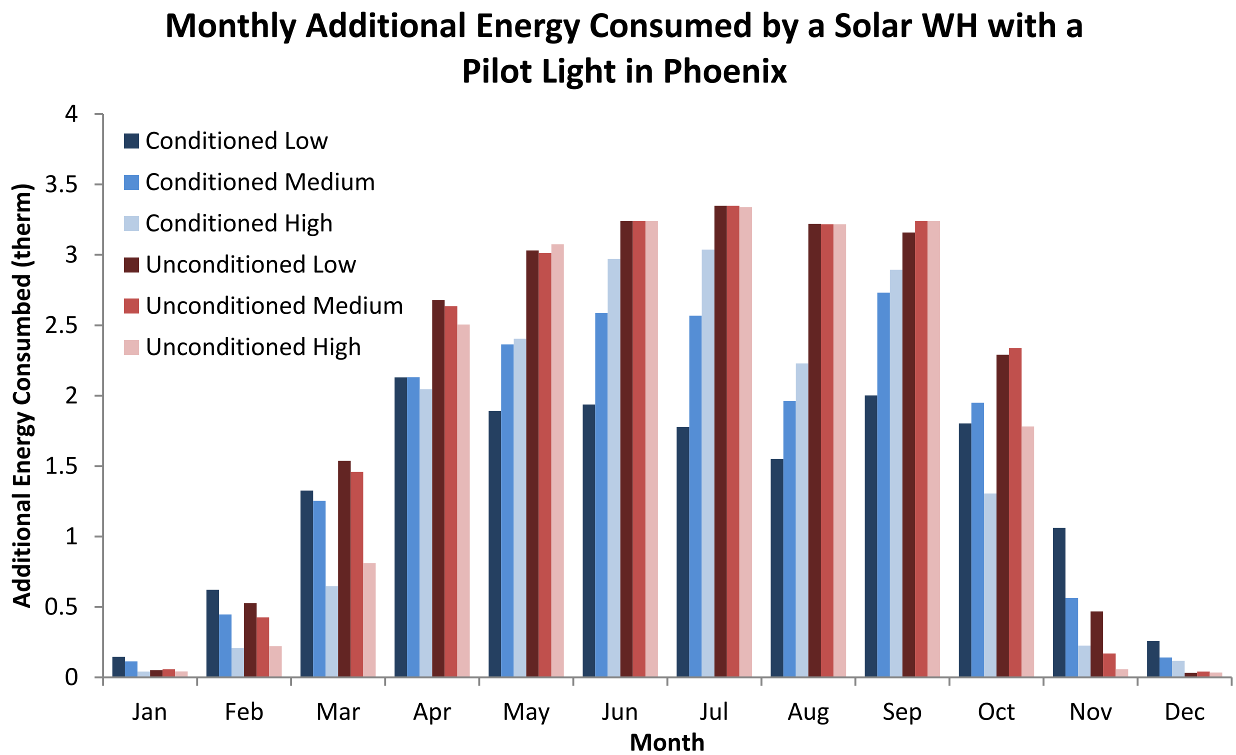

Figure 47. Monthly increase in site energy consumption from modeling a pilot light

For gas water heaters used alone, the energy consumption that comes from explicitly modeling a pilot light increases very little, except for cases where the water heater is in hot unconditioned space. However, when the gas water heater is used as the second tank in a solar water heating system, the increase in the annual energy consumption from modeling a pilot light is significant. The average increase is about 17% and the maximum increase is about 80%, which demonstrates that modeling the solar water heater without a pilot light can overpredict the savings associated with a solar water heater. This shows that the pilot light needs to be explicitly modeled for any solar water heater with a backup gas water heater that has a standing pilot. Many models (including those used by SRCC to rate the performance of solar water heaters) do not currently include a pilot light, and changes to these models are needed to more accurately predict savings, especially in hot, sunny locations.

Appendix C Hot Water Draw Volume for All Simulations in Parametric Study

Table 40. Water Heater Draw Volume in Gallons per Day for All Simulations in Parametric Study

Location	Installation Space	Draw Volume	Gas	Tankless	Condensing	Solar Gas	Electric	HPWH	Solar Electric
Chicago	Conditioned	Low	36.6	38.0	37.1	36.3	35.1	38.8	35.5
		Medium	52.2	54.2	53.0	52.0	50.0	55.4	51.4
		High	70.4	73.2	71.9	70.2	67.9	75.9	70.8
	Unconditioned	Low	36.7	38.2	37.1	36.4	35.2	38.7	35.6
		Medium	52.4	54.5	53.1	52.1	50.1	55.2	51.5
		High	70.6	73.5	71.8	70.4	67.9	75.7	70.9
Seattle	Conditioned	Low	36.4	37.9	36.9	36.1	34.8	38.5	35.6
		Medium	51.9	54.1	52.7	51.7	49.6	55.0	51.3
		High	70.0	73.1	71.4	69.8	67.3	75.4	70.4
	Unconditioned	Low	36.4	38.1	36.9	36.2	34.8	38.6	35.7
		Medium	52.0	54.3	52.8	51.8	49.7	55.2	51.4
		High	70.1	73.4	71.4	69.9	67.4	75.8	70.5
Atlanta	Conditioned	Low	34.3	36.4	34.9	33.6	32.6	36.6	31.3
		Medium	48.9	51.8	49.8	48.4	46.4	52.2	45.9
		High	65.8	69.8	67.3	65.6	62.7	71.5	64.1
	Unconditioned	Low	34.4	36.5	34.9	33.8	32.6	36.6	31.5
		Medium	49.0	52.0	49.8	48.5	46.4	52.4	46.1
		High	65.9	70.1	67.3	65.7	62.8	71.7	64.2
Los Angeles	Conditioned	Low	34.4	36.4	34.9	33.6	32.6	36.6	31.0
		Medium	49.0	52.0	49.9	48.6	46.5	52.3	46.3
		High	66.0	70.0	67.6	65.8	63.0	71.7	64.6

Location	Installation Space	Draw Volume	Gas	Tankless	Condensing	Solar Gas	Electric	HPWH	Solar Electric
Los Angeles	Unconditioned	Low	34.4	36.4	34.9	33.5	32.6	36.7	31.1
		Medium	49.0	51.9	49.9	48.4	46.5	52.5	46.4
		High	66.0	70.0	67.6	65.7	63.0	72.0	64.7
Houston	Conditioned	Low	32.5	34.9	33.2	31.8	30.7	34.8	29.0
		Medium	46.3	49.6	47.3	45.7	43.6	49.5	42.6
		High	62.2	66.8	63.7	61.8	58.9	67.8	59.3
	Unconditioned	Low	32.4	34.6	33.1	31.2	30.7	34.8	29.0
		Medium	46.1	49.2	47.1	44.6	43.6	49.6	42.6
		High	62.0	66.4	63.6	60.7	58.9	67.9	59.2
Phoenix	Conditioned	Low	29.6	32.4	30.2	28.3	27.7	31.7	24.7
		Medium	41.8	45.9	42.9	40.0	39.2	45.0	35.7
		High	56.1	61.6	57.7	54.1	52.7	61.3	49.6
	Unconditioned	Low	29.4	31.8	30.1	27.1	27.7	31.8	24.7
		Medium	41.6	45.1	42.6	37.9	39.2	45.1	35.7
		High	55.8	60.7	57.3	51.0	52.7	61.6	49.5

Appendix D Disaggregated Water Heater Energy Consumption

Table 41. Gas Storage Water Heater Site Energy Consumption, Tank Losses, and Delivered Energy

Location	WH Installation Location	Draw Volume	Water Heater Energy (therms)	Normalization Energy (therms)	Net Source Energy Consumption (MMBtu)	Tank Losses (therms)	Delivered Energy (therms)
Chicago	Conditioned Space	Low	140.5	0.4	15.4	35.0	73.4
		Med	180.2	0.6	19.7	35.0	104.1
		High	227.4	0.8	24.9	34.9	140.4
	Unconditioned Space	Low	155.8	0.6	17.1	46.8	73.3
		Med	195.5	0.7	21.4	46.8	104.0
		High	242.6	1.0	26.6	46.7	140.3
Seattle	Conditioned Space	Low	136.7	0.4	15.0	35.5	69.8
		Med	175.0	0.5	19.2	35.5	99.4
		High	220.1	0.8	24.1	35.5	134.2
	Unconditioned Space	Low	149.2	0.5	16.4	45.2	69.8
		Med	187.5	0.7	20.6	45.2	99.3
		High	232.7	1.0	25.5	45.2	134.1
Atlanta	Conditioned Space	Low	118.0	0.3	12.9	34.5	56.3
		Med	148.1	0.4	16.2	34.5	79.8
		High	184.4	0.4	20.2	34.5	107.8
	Unconditioned Space	Low	126.0	0.4	13.8	40.8	56.3
		Med	156.4	0.4	17.1	40.9	79.7
		High	192.6	0.4	21.1	40.8	107.6
Los Angeles	Conditioned Space	Low	116.4	0.3	12.7	34.1	55.4
		Med	146.9	0.3	16.1	34.1	79.0
		High	182.9	0.4	20.0	34.1	106.7
	Unconditioned Space	Low	117.3	0.2	12.8	34.9	55.4
		Med	147.9	0.4	16.2	34.9	79.0
		High	183.8	0.4	20.1	34.8	106.7
Houston	Conditioned Space	Low	104.6	0.2	11.4	33.6	46.9
		Med	129.8	0.3	14.2	33.7	66.2
		High	159.9	0.2	17.5	33.7	89.4
	Unconditioned Space	Low	102.3	0.2	11.2	31.7	47.0
		Med	126.9	0.2	13.9	31.3	66.4
		High	156.8	0.2	17.1	31.2	89.6
Phoenix	Conditioned Space	Low	93.6	0.2	10.2	33.5	38.5
		Med	113.4	0.2	12.4	33.6	53.7
		High	137.9	0.2	15.1	33.6	72.6
	Unconditioned Space	Low	90.3	0.1	9.9	30.3	39.2
		Med	108.6	0.2	11.9	29.2	54.4
		High	132.1	0.2	14.4	28.5	73.2

Table 42. Tankless Water Heater Site Energy Consumption, Tank Losses, and Delivered Energy*

Location	WH Installation Location	Draw Volume	Water Heater Energy (therms)	Normalization Energy (therms)	Secondary Energy (kWh)	Change in Space Heating Energy (therms)	Change in Space Cooling Energy (kWh)	Change in Fan Energy (kWh)	Net Source Energy (MMBtu)	Tank Losses (therms)	Delivered Energy (therms)
Chicago	Conditioned Space	Low	86.6	8.7	96	17.0	–74	3	12.5	1.1	68.0
		Med	122.7	12.0	99	16.8	–71	3	16.9	1.6	96.5
		High	166.1	15.3	103	16.6	–70	3	22.0	2.0	131.0
	Unconditioned Space	Low	87.0	11.3	124	5.3	–22	1	12.5	3.8	66.2
		Med	123.1	15.3	119	4.9	–22	1	16.8	4.7	94.3
		High	166.6	19.3	119	4.7	–21	1	21.9	5.5	128.4
Seattle	Conditioned Space	Low	82.9	8.7	96	19.5	–26	14	13.1	1.5	64.8
		Med	117.8	11.9	99	19.2	–26	14	17.3	2.0	92.4
		High	159.6	15.1	103	19.0	–25	14	22.2	2.4	125.5
	Unconditioned Space	Low	83.2	10.9	95	5.8	–9	4	11.9	3.6	63.3
		Med	118.2	14.7	99	5.7	–9	4	16.2	4.6	90.5
		High	160.0	18.5	103	5.6	–9	4	21.2	5.3	123.3
Atlanta	Conditioned Space	Low	67.3	7.9	96	11.2	–90	–2	9.5	2.1	52.0
		Med	95.2	10.7	99	11.0	–89	–2	12.9	2.8	73.9
		High	128.8	13.5	103	10.8	–88	–2	16.9	3.3	100.4
	Unconditioned Space	Low	67.6	9.3	96	2.6	–19	0	9.6	3.6	51.1
		Med	95.5	12.5	99	2.6	–19	0	13.0	4.5	72.7
		High	129.2	15.6	103	2.5	–18	0	17.1	5.2	99.1
Los Angeles	Conditioned Space	Low	66.2	7.6	96	8.3	–105	–8	8.8	2.1	51.2
		Med	94.5	10.3	99	8.2	–104	–8	12.2	2.7	73.3
		High	127.7	12.9	103	8.0	–100	–8	16.2	3.2	99.6
	Unconditioned Space	Low	66.2	7.8	96	0.8	–5	0	9.2	2.3	51.1
		Med	94.5	10.4	99	0.8	–5	0	12.6	3.0	73.2
		High	127.8	13.1	103	0.8	–5	0	16.6	3.5	99.4
Houston	Conditioned Space	Low	56.2	7.2	95	6.7	–155	–18	6.8	2.6	42.9
		Med	79.5	9.6	99	6.5	–151	–17	9.7	3.3	61.1
		High	107.4	12.0	103	6.4	–148	–17	13.0	3.8	83.0
	Unconditioned Space	Low	56.1	6.8	42	0.6	–10	–1	7.3	2.1	43.1
		Med	79.4	9.0	38	0.6	–10	–1	10.0	2.5	61.3
		High	107.3	11.4	31	0.5	–10	–1	13.3	3.0	83.2
Phoenix	Conditioned Space	Low	46.4	7.0	95	5.9	–142	–12	5.8	3.1	34.8
		Med	64.8	9.2	99	5.8	–136	–11	8.2	3.9	48.9
		High	87.5	11.4	103	5.7	–133	–10	10.9	4.5	66.6
	Unconditioned Space	Low	46.1	6.1	40	0.5	–7	0	6.1	1.8	35.1
		Med	64.4	8.1	34	0.4	–7	0	8.3	2.3	49.4
		High	87.0	10.1	29	0.4	–7	0	10.9	2.6	67.1

*A negative number indicates savings relative to the base case

Table 43. Condensing Water Heater Site Energy Consumption, Tank Losses, and Delivered Energy*

Location	WH Installation Location	Draw Volume	Water Heater Energy (therms)	Normalization Energy (therms)	Secondary Energy (kWh)	Change in Space Heating Energy (therms)	Change in Space Cooling Energy (kWh)	Change in Fan Energy (kWh)	Net Source Energy (MMBtu)	Tank Losses (therms)	Delivered Energy (therms)
Chicago	Conditioned Space	Low	94.6	1.3	143	2.3	–5	1	12.3	21.6	72.9
		Med	124.2	1.8	144	2.6	–6	1	15.6	20.8	103.5
		High	159.5	3.1	146	3.2	–9	1	19.7	20.1	139.4
	Unconditioned Space	Low	103.8	1.2	144	0.0	–1	0	13.1	30.8	73.0
		Med	133.4	2.0	145	0.2	–2	0	16.5	30.0	103.4
		High	168.8	2.8	146	0.3	–2	0	20.4	29.3	139.5
Seattle	Conditioned Space	Low	91.6	1.2	143	1.9	0	–10	11.9	22.2	69.4
		Med	120.0	1.9	144	2.8	0	–9	15.2	21.3	98.7
		High	153.9	3.1	145	3.0	–1	–9	19.0	20.7	133.3
	Unconditioned Space	Low	99.1	1.2	144	0.1	0	0	12.6	29.7	69.4
		Med	127.8	1.9	145	0.1	0	0	15.8	29.0	98.9
		High	161.6	2.8	146	0.4	0	0	19.7	28.2	133.4
Atlanta	Conditioned Space	Low	77.7	1.0	143	0.1	2	1	10.3	21.8	56.0
		Med	100.3	1.4	144	0.8	–1	1	12.9	21.1	79.3
		High	127.5	1.9	145	0.9	–1	2	15.9	20.5	107.0
	Unconditioned Space	Low	82.7	1.0	143	0.0	0	0	10.8	26.8	56.0
		Med	105.3	1.4	144	0.1	–1	0	13.3	26.0	79.3
		High	132.4	2.1	145	0.0	–1	0	16.3	25.5	106.9
Los Angeles	Conditioned Space	Low	76.7	0.9	143	0.3	–4	0	10.1	21.7	55.0
		Med	99.4	1.4	144	0.6	–9	–1	12.6	20.9	78.5
		High	126.3	2.1	145	0.8	–11	–1	15.6	20.4	106.0
	Unconditioned Space	Low	77.1	1.0	143	0.0	0	0	10.2	22.1	55.0
		Med	99.8	1.4	144	0.0	–1	0	12.7	21.4	78.5
		High	126.8	2.1	145	0.0	–1	0	15.7	20.9	106.0
Houston	Conditioned Space	Low	68.1	0.9	143	0.6	–9	–1	9.1	21.6	46.5
		Med	86.7	1.3	143	0.7	–14	–1	11.1	21.0	65.7
		High	109.3	1.6	144	0.8	–20	–2	13.6	20.5	88.8
	Unconditioned Space	Low	65.5	0.7	142	0.0	–2	0	8.8	19.0	46.6
		Med	84.3	1.1	143	0.0	–2	0	10.9	18.5	65.8
		High	107.0	1.5	144	–0.1	–2	0	13.5	18.1	88.9
Phoenix	Conditioned Space	Low	60.0	0.8	142	0.3	–3	0	8.3	21.8	38.2
		Med	74.6	1.1	143	0.4	–5	0	9.9	21.4	53.3
		High	92.9	1.4	143	0.5	–10	0	11.9	20.9	72.0
	Unconditioned Space	Low	54.9	0.8	142	0.0	–2	0	7.7	16.8	38.2
		Med	69.7	0.9	143	0.0	–2	0	9.3	16.3	53.4
		High	88.1	1.1	143	0.1	–2	0	11.4	15.9	72.1

Table 44. Solar Gas Water Heater Site Energy Consumption, Tank Losses, and Delivered Energy*

Location	WH Installation Location	Draw Volume	WH Energy (therms)	Normalization Energy (therms)	Secondary Energy (kWh)	Change in Space Heating Energy (therms)	Change in Space Cooling Energy (kWh)	Change in Fan Energy (kWh)	Net Source Energy (MMBtu)	Net Losses to Ambient** (therms)	Delivered Energy (therms)
Chicago	Conditioned Space	Low	80.1	0.2	96	–3.8	50	5	10.1	46.3	73.8
		Med	106.6	0.2	102	–1.9	32	3	13.0	42.7	104.3
		High	144.7	0.4	107	–0.9	16	1	17.2	40.0	140.5
	Unconditioned Space	Low	97.7	0.3	97	–26.0	120	–4	10.3	61.6	73.6
		Med	125.3	0.4	103	–24.4	102	–6	13.4	58.4	104.2
		High	164.3	0.5	107	–23.7	84	–8	17.5	56.1	140.4
Seattle	Conditioned Space	Low	82.9	0.3	87	–3.7	30	1	10.0	45.1	70.1
		Med	111.0	0.3	92	–2.1	24	2	13.3	42.4	99.7
		High	147.8	0.4	96	–1.0	13	1	17.3	40.0	134.3
	Unconditioned Space	Low	97.7	0.4	88	–26.1	58	–15	9.4	57.8	69.9
		Med	126.5	0.4	93	–24.3	52	–14	12.7	55.4	99.5
		High	164.3	0.6	97	–23.4	44	–15	16.9	53.4	134.2
Atlanta	Conditioned Space	Low	56.1	0.1	100	–7.1	90	7	7.6	54.6	57.2
		Med	69.8	0.2	107	–5.5	68	6	9.1	50.1	80.5
		High	94.7	0.2	112	–4.8	47	3	11.7	46.7	108.0
	Unconditioned Space	Low	63.8	0.2	101	–20.3	177	6	8.0	62.1	57.0
		Med	78.6	0.2	108	–19.2	156	4	9.6	58.1	80.2
		High	104.2	0.3	113	–18.2	135	2	12.3	54.9	107.8
Los Angeles	Conditioned Space	Low	49.7	0.1	102	–5.1	148	17	8.0	56.4	56.5
		Med	61.0	0.2	109	–4.1	109	13	8.9	51.0	79.7
		High	84.0	0.3	113	–3.0	84	10	11.3	47.1	107.0
	Unconditioned Space	Low	52.8	0.1	101	–0.6	11	1	7.0	57.1	57.0
		Med	63.9	0.2	109	–0.5	8	1	8.3	51.9	80.3
		High	86.1	0.2	113	–0.4	6	0	10.7	47.7	107.4
Houston	Conditioned Space	Low	51.8	0.1	99	–3.8	184	26	8.8	56.0	47.9
		Med	60.9	0.2	107	–2.8	151	22	9.6	51.7	67.2
		High	80.5	0.2	111	–2.1	127	19	11.5	48.6	90.2
	Unconditioned Space	Low	56.9	0.1	96	–0.3	10	1	7.4	54.3	50.1
		Med	65.1	0.2	106	–0.2	8	1	8.4	49.7	69.8
		High	83.3	0.2	111	–0.3	6	1	10.4	46.0	92.7
Phoenix	Conditioned Space	Low	43.5	0.1	87	–3.8	244	33	8.5	63.6	40.5
		Med	47.6	0.1	98	–3.3	245	34	9.2	62.7	56.8
		High	57.7	0.1	105	–2.6	235	34	10.3	60.5	76.2
	Unconditioned Space	Low	48.7	0.1	84	–0.4	13	1	6.4	58.2	43.9
		Med	53.3	0.2	96	–0.4	14	2	7.1	56.6	61.7
		High	64.0	0.2	104	–0.3	12	1	8.3	53.9	82.1

*A negative number indicates savings relative to the base case
**Net losses include losses from both tanks and the collector loop

Table 45. Electric Storage Water Heater Site Energy Consumption, Tank Losses, and Delivered Energy

Location	WH Installation Location	Draw Volume	Water Heater Energy (kWh)	Normalization Energy (kWh)	Net Source Energy (MMBtu)	Tank Losses (kWh)	Delivered Energy (kWh)
Chicago	Conditioned Space	Low	2503	12	28.9	340	2164
		Med	3405	13	39.2	336	3070
		High	4464	33	51.6	332	4133
	Unconditioned Space	Low	2641	13	30.5	479	2163
		Med	3544	13	40.8	475	3069
		High	4603	34	53.2	472	4132
Seattle	Conditioned Space	Low	2411	7	27.8	350	2062
		Med	3280	10	37.8	346	2934
		High	4295	30	49.7	342	3953
	Unconditioned Space	Low	2526	7	29.1	465	2062
		Med	3395	10	39.1	462	2934
		High	4411	31	51.0	458	3953
Atlanta	Conditioned Space	Low	2017	2	23.2	350	1668
		Med	2706	5	31.1	347	2359
		High	3528	9	40.6	345	3183
	Unconditioned Space	Low	2092	2	24.0	425	1668
		Med	2781	6	32.0	422	2359
		High	3603	9	41.5	420	3183
Los Angeles	Conditioned Space	Low	1997	1	22.9	357	1640
		Med	2690	5	30.9	354	2336
		High	3505	12	40.4	352	3153
	Unconditioned Space	Low	2044	1	23.5	404	1640
		Med	2737	5	31.5	402	2336
		High	3552	13	40.9	400	3153
Houston	Conditioned Space	Low	1742	0	20.0	352	1390
		Med	2313	3	26.6	350	1963
		High	3000	3	34.5	349	2651
	Unconditioned Space	Low	1751	0	20.1	362	1390
		Med	2323	3	26.7	360	1963
		High	3009	3	34.6	358	2651
Phoenix	Conditioned Space	Low	1502	0	17.2	357	1145
		Med	1954	1	22.4	355	1599
		High	2513	1	28.9	354	2159
	Unconditioned Space	Low	1466	0	16.8	321	1146
		Med	1918	1	22.0	319	1599
		High	2477	1	28.5	318	2159

Table 46. Heat Pump Water Heater Energy Site Consumption, Tank Losses, and Delivered Energy*

Location	WH Installation Location	Draw Volume	Water Heater Energy (kWh)**	Normalization Energy (kWh)	Change in Space Heating Energy (kWh)	Change in Space Cooling Energy (kWh)	Change in Fan Energy (kWh)	Net Source Energy (MMBtu)	Tank Losses (kWh)	Delivered Energy (kWh)
Chicago	Conditioned Space	Low	1128	125	368	–172	5	16.7	346	2094
		Med	1518	154	500	–225	8	22.5	333	2981
		High	2225	314	567	–274	6	32.6	322	3968
	Unconditioned Space	Low	1718	123	–3	–55	–5	20.4	523	2099
		Med	2295	157	10	–66	–6	27.4	514	2985
		High	3110	311	13	–76	–7	38.5	506	3979
Seattle	Conditioned Space	Low	1054	113	343	–66	19	16.8	360	1996
		Med	1401	139	471	–80	28	22.5	348	2853
		High	2069	292	542	–91	32	32.7	338	3797
	Unconditioned Space	Low	1248	126	64	–24	3	16.3	518	1992
		Med	1673	163	89	–30	5	21.8	509	2846
		High	2383	328	104	–33	5	32.0	501	3787
Atlanta	Conditioned Space	Low	840	91	184	–226	–12	10.1	365	1612
		Med	1070	109	253	–294	–14	12.9	357	2290
		High	1543	216	299	–351	–16	19.4	349	3055
	Unconditioned Space	Low	952	98	2	–70	–9	11.2	465	1610
		Med	1219	126	7	–80	–10	14.5	457	2285
		High	1734	239	12	–88	–10	21.7	450	3048
Los Angeles	Conditioned Space	Low	791	84	184	–70	9	11.5	376	1588
		Med	1000	104	255	–89	14	14.7	368	2267
		High	1458	208	306	–102	17	21.7	360	3031
	Unconditioned Space	Low	901	96	4	–3	0	11.5	445	1584
		Med	1171	123	5	–5	0	14.8	440	2263
		High	1687	242	7	–4	0	22.2	433	3023
Houston	Conditioned Space	Low	674	70	129	–222	–16	7.3	373	1343
		Med	836	84	161	–316	–25	8.5	365	1903
		High	1186	159	199	–368	–27	13.2	359	2547
	Unconditioned Space	Low	748	76	4	–4	0	9.5	392	1341
		Med	935	96	5	–8	–1	11.8	388	1900
		High	1320	176	5	–10	–1	17.1	384	2545
Phoenix	Conditioned Space	Low	631	62	88	–175	–18	6.7	381	1101
		Med	777	76	115	–240	–26	8.1	374	1539
		High	1041	132	140	–296	–33	11.3	369	2065
	Unconditioned Space	Low	670	70	3	–2	0	8.5	343	1099
		Med	839	90	4	–4	0	10.7	340	1536
		High	1132	159	3	–6	0	14.8	336	2060

*A negative number indicates savings relative to the base case

**Water heater energy includes all energy consumed by the compressor, resistance elements, fan, and controls

Table 47. Solar Electric Water Heater Site Energy Consumption, Tank Losses, and Delivered Energy*

Location	WH Installation Location	Draw Volume	Water Heater Energy (kWh)	Normalization Energy (kWh)	Secondary Energy (kWh)	Change in Space Heating Energy (kWh)	Change in Space Cooling Energy (kWh)	Change in Fan Energy (kWh)	Net Source Energy (MMBtu)	Net Losses to Ambient** (kWh)	Delivered Energy (kWh)
Chicago	Conditioned Space	Low	1113	36	106	–8	–2	0	14.3	368	2165
		Med	1783	48	116	–7	–8	0	22.2	333	3055
		High	2692	122	122	–3	–12	0	33.5	306	4087
	Unconditioned Space	Low	1194	39	107	–46	7	–1	14.9	439	2163
		Med	1872	51	116	–41	3	–2	23.0	405	3052
		High	2784	128	123	–36	–1	–2	34.4	378	4083
Seattle	Conditioned Space	Low	1150	36	97	19	4	2	15.0	343	2054
		Med	1846	49	105	23	2	2	23.3	317	2918
		High	2716	115	111	26	0	2	34.1	293	3907
	Unconditioned Space	Low	1217	38	98	–9	6	0	15.5	403	2051
		Med	1919	51	106	–8	3	0	23.8	377	2916
		High	2794	119	111	–4	4	0	34.7	353	3904
Atlanta	Conditioned Space	Low	526	9	107	–21	–1	–2	7.1	485	1711
		Med	926	11	119	–18	–10	–3	11.8	448	2381
		High	1582	41	125	–16	–14	–3	19.7	417	3173
	Unconditioned Space	Low	560	10	107	–39	10	–2	7.4	522	1706
		Med	968	12	119	–36	10	–2	12.3	486	2377
		High	1627	42	125	–34	3	–3	20.2	456	3171
Los Angeles	Conditioned Space	Low	368	5	108	–6	27	2	5.8	520	1685
		Med	751	10	119	–2	20	2	10.3	474	2351
		High	1381	37	123	1	17	1	17.9	442	3143
	Unconditioned Space	Low	395	5	108	0	1	0	5.8	553	1683
		Med	784	10	119	0	1	0	10.5	510	2350
		High	1418	39	123	0	1	0	18.2	479	3142
Houston	Conditioned Space	Low	405	6	105	–4	52	7	6.6	503	1444
		Med	691	8	116	0	44	7	9.9	467	1994
		High	1206	23	122	2	37	6	16.0	441	2659
	Unconditioned Space	Low	426	6	105	0	1	0	6.2	495	1445
		Med	711	8	115	0	1	0	9.6	460	2000
		High	1222	23	122	1	1	0	15.7	433	2664
Phoenix	Conditioned Space	Low	172	2	88	–6	54	9	3.7	540	1212
		Med	317	3	100	–5	57	10	5.5	536	1668
		High	627	9	110	–2	59	11	9.3	528	2226
	Unconditioned Space	Low	186	3	87	0	2	0	3.2	494	1215
		Med	333	3	99	0	2	0	5.0	483	1670
		High	647	9	109	0	2	0	8.8	469	2225

*A negative number indicates savings relative to the base case
**Net losses include losses from the tank and the collector loop

Appendix E Sensitivity Analysis of Life Cycle Costs and Breakeven Costs

Sensitivity of Life Cycle Costs to Solar Water Heater Installed Cost

Given the wide variability in solar water heater installation costs, the LCC analysis was also performed assuming that a low-cost solar water heater with the same performance was installed. Incentives were not considered in this case, as incentive levels would likely change if the average installed cost of solar water heaters dropped significantly. In this case, a low-cost system was assumed to have a net installed cost of $3000 in all cases. This installed cost is the upper end of a goal for research and development efforts underway at the National Renewable Energy Laboratory (22). The most cost-effective options with this new solar water heating price are given in Table 48 through Table 51. Situations where solar water heaters are now the most cost-effective option are bold.

For gas water heaters, solar water heaters become cost effective in many new construction medium- and high-use cases. However, in retrofit cases they are cost effective only in high-use cases in unconditioned spaces or in locations where the gas rates are relatively high. For electric water heaters in new construction homes, solar becomes cost effective only in low-use cases in Los Angeles, which has very high electricity rates. In retrofit homes solar becomes cost effective in more cases because HPWHs have a higher net installed cost in retrofit homes.

Table 48. Lowest LCC Gas Water Heating Option for New Construction Homes With No Incentives for the Low-Cost Solar Case

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	**Solar Gas**	**Solar Gas**	Tankless	**Solar Gas**	**Solar Gas**
Seattle	Gas Storage	Gas Storage	**Solar Gas**	Tankless	**Solar Gas**	**Solar Gas**
Atlanta	**Solar Gas**	**Solar Gas**	**Solar Gas**	Tankless	**Solar Gas**	**Solar Gas**
Los Angeles	Tankless	**Solar Gas**	**Solar Gas**	Tankless	**Solar Gas**	**Solar Gas**
Houston	Tankless	Tankless	Tankless	Tankless	**Solar Gas**	**Solar Gas**
Phoenix	Tankless	Tankless	**Solar Gas**	Tankless	Tankless	**Solar Gas**

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, blue denotes two other options within 10%, and purple denotes three other options within 10%

Table 49. Lowest LCC Electric Water Heating Option for New Construction Homes With No Incentives for the Low-Cost Solar Case

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	**Solar Electric**	HPWH	HPWH	**Solar Electric**	HPWH	HPWH
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	HPWH	HPWH	HPWH	Electric Storage	HPWH	HPWH

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Table 50. Lowest LCC Gas Water Heating Option for Retrofit Homes With No Incentives for the Low-Cost Solar Case

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	**Solar Gas**
Seattle	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	**Solar Gas**
Atlanta	Gas Storage	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**	**Solar Gas**
Los Angeles	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	**Solar Gas**
Houston	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage	Gas Storage
Phoenix	Gas Storage	Gas Storage	**Solar Gas**	Gas Storage	Gas Storage	**Solar Gas**

Yellow denotes no option is within 10% of being cost effective and green denotes one other option within 10%

Table 51. Lowest LCC Electric Water Heating Option for Retrofit Homes With No Incentives for the Low-Cost Solar Case

Location	Conditioned Space			Unconditioned Space		
	Low	Medium	High	Low	Medium	High
Chicago	HPWH	HPWH	HPWH	**Solar Electric**	HPWH	HPWH
Seattle	Electric Storage	HPWH	HPWH	HPWH	HPWH	HPWH
Atlanta	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Los Angeles	**Solar Electric**	**Solar Electric**	**Solar Electric**	**Solar Electric**	**Solar Electric**	**Solar Electric**
Houston	HPWH	HPWH	HPWH	HPWH	HPWH	HPWH
Phoenix	Electric Storage	HPWH	HPWH	Electric Storage	**Solar Electric**	**Solar Electric**

Yellow denotes no option is within 10% of being cost effective, green denotes one other option within 10%, and blue denotes two other options within 10%

Sensitivity of Life Cycle Costs to Utility Rates

A study was performed to determine the sensitivity of the water heater LCC to the assumed utility rates. Although the utility rates used here are reasonable for these locations, rates are volatile and can change significantly in a relatively short time. To determine how changes in utility rates would change which water heating option would be most cost effective, plots were created of the water heater LCC at different utility rates. In this sensitivity study, only medium-use cases for water heaters in unconditioned spaces in the retrofit scenario with no incentives were considered.

For gas water heaters, the LCC depends on both the gas rate and the electricity rate. Tankless, condensing, and solar water heaters all consume both electricity and gas. The change in space conditioning energy consumption also includes some electricity use. In this case, gas rates of $0.00 and $10/therm and electricity rates of $0.00 and $0.30/kWh were considered. The lowest LCC option for each climate is shown in Figure 48.

For all locations, a gas water heater is the most cost-effective option in the case of free energy. Solar water heaters are cost effective only at the highest gas rates in Atlanta. However, if rates higher than $10/therm were considered, solar water heaters would appear as the least cost option in more locations. Condensing water heaters and tankless water heaters are the lowest cost options for gas rates of $2.00–$4.00/therm, depending on the location.

The electricity rate also plays a role in these cases. The condensing water heater has a standby power consumption of 16 W; the tankless water heater has a standby power consumption of 10 W. This standby power consumption leads to the sensitivity of the LCC to the electricity rate. The impact of the higher standby power consumption of condensing water heaters over tankless water heaters can be seen in Atlanta and Los Angeles in particular, where the slope of the line separating typical gas storage water heaters changes depending on whether tankless or condensing water heaters are the most cost-effective option. Condensing water heaters tend to save more energy over tankless water heaters in colder locations with higher loads. Thus, condensing water heaters are the lowest cost option at high gas rates regardless of the electricity rate in Chicago and tankless water heaters are the most cost-effective option in Phoenix for most electricity rates.

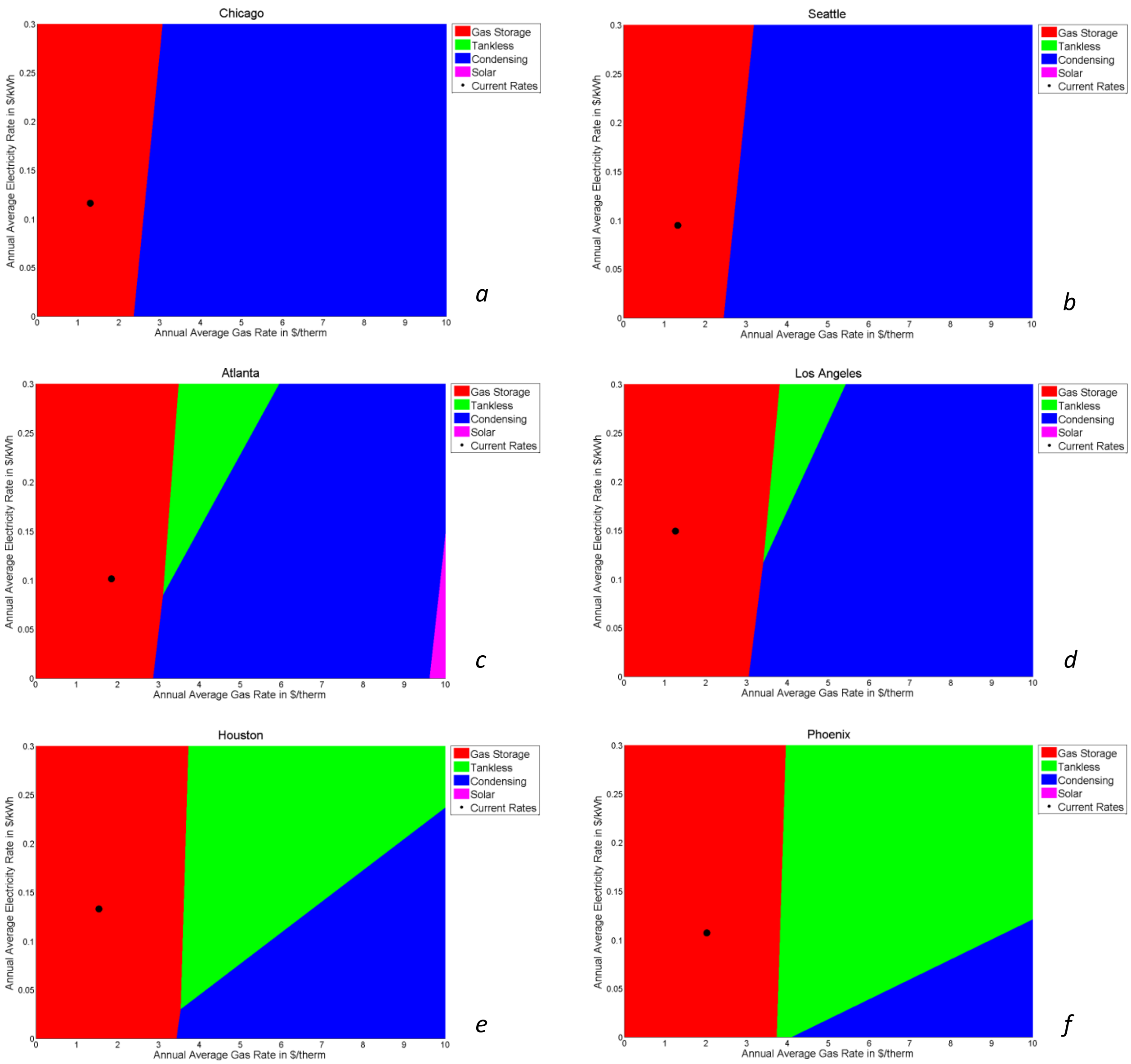

Figure 48a–f. Lowest LCC gas water heating option for all locations at different rates for a retrofit medium-use home with the water heater in unconditioned space

For electric water heaters, the LCC depends only on the electricity rate, because these are assumed to be installed only in homes without gas. The LCC of each electric water heating option in all climates for the retrofit case with medium use and the water heater located in unconditioned space is shown in Figure 49. In this case, a regular electric storage water heater is the lowest cost option for the case of free electricity and a HPWH is the most cost-effective option at the high cost case of $0.30/kWh. Because the HPWH and the solar water heater save comparable energy and the solar water heater has a higher installed cost, the solar water heater is never the most cost-effective option for the range of rates considered here. However, in some cases a solar water heater would be the most cost effective option if even higher electricity rates are considered. This is especially apparent in Los Angeles, where the solar water heater and HPWH LCCs are coming closer together as the electricity rates increase.

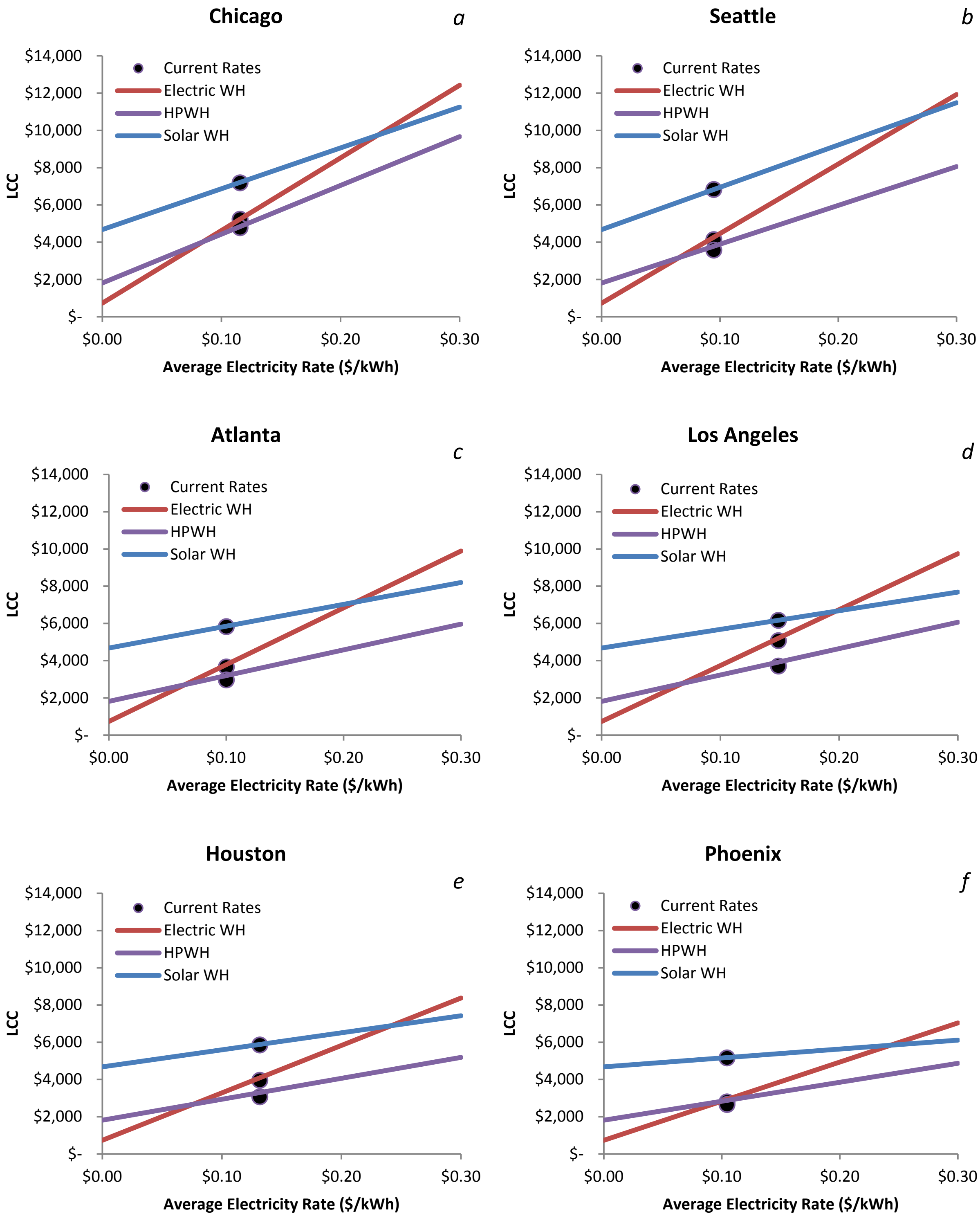

Figure 49a–f. LCC of electric water heating options for all locations at different utility rates

Sensitivity of Breakeven Costs to Baseline Water Heater Installed Costs

Although the breakeven cost includes no assumptions about the installed cost of the new water heater, an assumption of the cost of the baseline water heater (either gas or electric storage) is required. However, the installed cost of a gas or electric water heater can change drastically (especially for gas) from home to home. The breakeven cost was recalculated for a range of baseline water heater costs for medium-use homes (with the water heater installed in conditioned space) (see Figure 50) to determine the effect of the assumed installed cost on the breakeven cost.

A reasonable range of installed costs for gas and electric water heaters was determined based on the most recent DOE water heater rulemaking (7). The technical support documents provide the range of installed costs and average installed costs for each water heater. For this sensitivity study, the 5th and 95th percentile installed costs for gas and electric water heaters were used to define the range of installed costs. For gas water heaters, the 5th percentile cost is $736 and the 95th percentile cost is $1,883. For electric water heaters, these costs are $445 and $722, respectively.

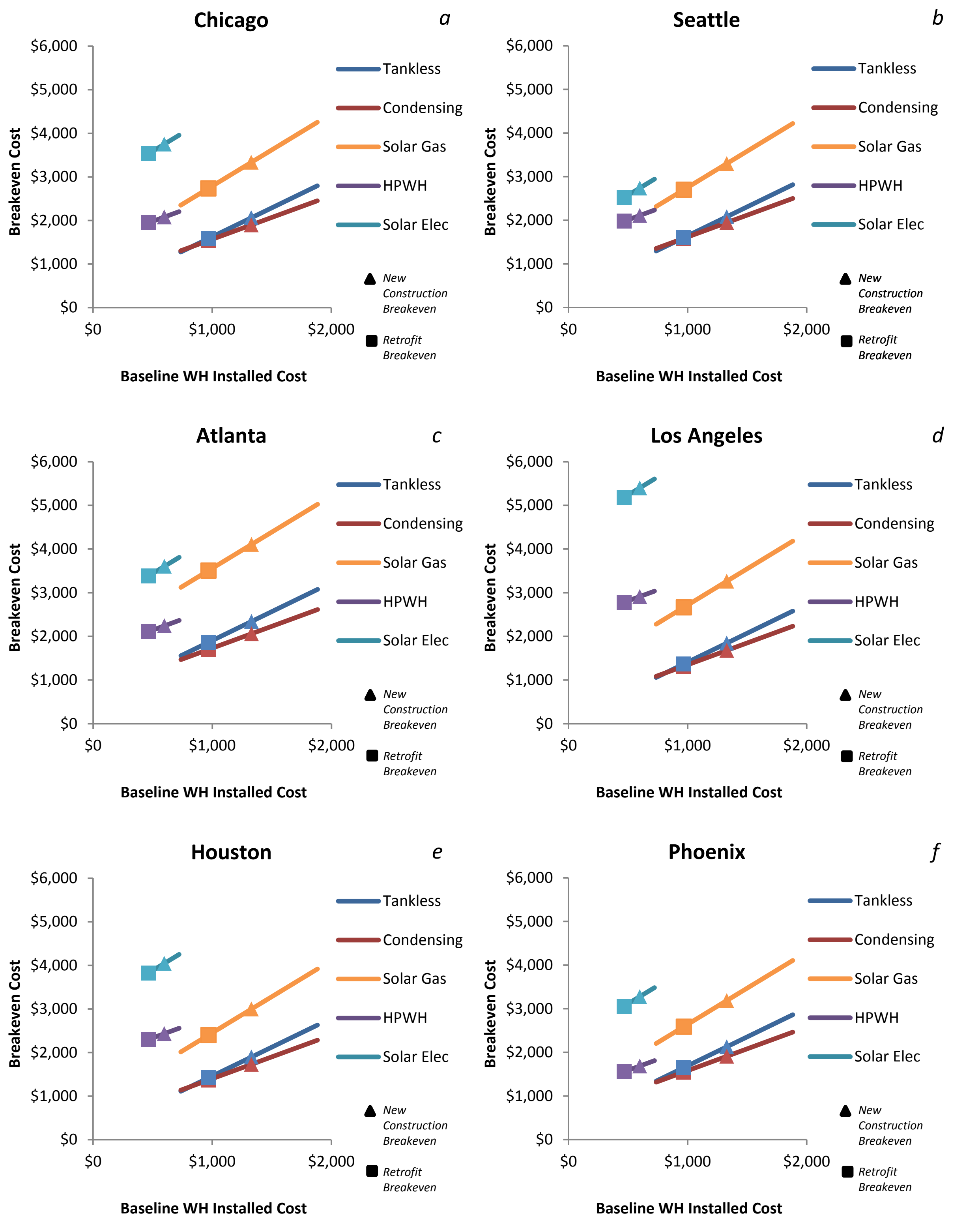

Figure 50 a–f. Breakeven cost at different baseline water heater costs for medium use homes with the water heater in conditioned space

Appendix F Water Heater Installation Cost Determination

To determine the installation cost of the non-solar water heaters the DOE water heater rulemaking was used (7). As part of the rulemaking installation cost determination, data from the 2005 Residential Energy Consumption Survey (RECS) (1) were used to determine where a water heater would likely be installed and if any cost adders (for example, additional labor for an attic installation) would apply to that particular home. In this case, 2,166 homes were used. Each home has a different weighting factor that corresponds to the number of homes that particular home represents. After all the appropriate cost adders are applied to the installation cost in each home, the weighting factor is taken into account and the weighted average net installation cost is calculated.

In cases where cost adders are randomly applied to a certain percentage of homes in the rulemaking, this cost adder is also randomly applied to that percentage of homes before the weighting factor is taken into account. This causes the percentage of homes to which it is applied to vary slightly from the percentage described in the rulemaking. A good example of this is the case of a condensate neutralizer for condensing water heaters where it is estimated in the rulemaking that 25% of homes require a filter. This is randomly applied to 25% of the homes before the weighting, but after the weighting factor is taken into account this is applied to 24.6% of homes. In general, the deviations from what is prescribed in the rulemaking are within 1% and are therefore considered to not significantly impact the results of the economic analysis performed here. Applying the cost adders in this way is consistent with the rulemaking analysis, but there may be slight differences in the actual percentage of homes to which costs are applied because of the slight differences in methodology described below.

The methodology used here does vary slightly from the rulemaking. For the rulemaking, Monte Carlo methods are used. In each simulation, one house is randomly selected from the RECS dataset. As a result, homes are considered multiple times and the results vary slightly from using each home exactly once as was done here. For this work, regional cost multipliers are not taken into account. Cost adders which may not necessarily correspond to the exact situations simulated here (for example, an attic installation cost adder is included although water heaters were not simulated in an attic) in this cost determination to get an installation cost that is close to the national average for each water heater instead of being specific to the particular case simulated here. The cost adders applied here, the percentage of the total housing stock to which they are applied, and the net installation cost for each water heater covered by the rulemaking in new construction homes are provided in Table 52; these costs for retrofit homes are provided in Table 53.

In each case, the rulemaking specifies a basic installation cost that is applied to all homes. A large tank adder is applied to homes where a large tank was currently installed, where a large tank is defined as being larger than 65 gallons. This cost adder is not applied to tankless water heaters or HPWHs. For HPWHs, a larger tank volume may lead to a significant increase in efficiency, as the additional volume may allow the water heater to recover with just the heat pump in situations. Conversely, a 50-gallon HPWH may need to use the electric resistance elements to recover in a reasonable time. An attic installation cost adder is applied to homes where the water heater is assumed to be installed in the attic for all technologies except tankless water heaters. The attic installation cost adder is additional labor in the case of attic installations. This labor is assumed to come primarily from the difficulty of bringing a water heater up to the attic. For a tankless water heater, considerably less effort is required to move it up to an attic, because it is small and no cost adder is applied.

Table 52. Net Installation Cost for Water Heaters in New Construction Homes

	Gas Storage		Tankless		Condensing		Electric Storage		HPWH	
	Cost ($)	% of Homes	Cost ($)	% of Homes	Cost ($)	% of Homes	Cost ($)	% of Homes	Cost ($)	% of Homes
Basic Installation	401.75	100%	806.20	100%	401.75	100%	178.53	100%	178.53	100%
Large Tank Adder	37.95	3.9%			37.95	3.9%	37.95	12.0%	37.95	2.5%
Attic Installation Adder	37.95	2.5%			37.95	2.5%	37.95	2.5%	63.50	100%
Stainless Steel Vent Connector	89.60	23.2%								100%
Venting, Common Vent	241.21	61.1%								
Venting, Separate Vent	788.67	38.9%								
PVC Venting					193.43	100%				
Condensate Disposal					86.00	24.6%				
HPWH Cost Adder									63.50	100%
Drain Pan Increase									1.90	100%
Net Cost	$879.12		$806.20		$618.80		$184.02		$244.89	

Table 53. Net Installation Cost for Water Heaters in Retrofit Homes

	Gas Storage		Tankless		Condensing		Electric Storage		HPWH	
	Cost ($)	% of Homes	Cost ($)	% of Homes	Cost ($)	% of Homes	Cost ($)	% of Homes	Cost ($)	% of Homes
Basic Installation	458.04	100%	1272.83	100%	458.04	100%	303.87	100%	303.87	100%
Large Tank Adder	75.90	3.9%			75.90	3.9%	75.90	12.0%		
Attic Installation Adder	75.90	2.5%			75.90	2.5%	75.90	2.5%	75.90	2.5%
Stainless Steel Vent Connector	238.04	23.3%								
Electric Outlet			177.61	38.89%	177.61	38.9%				
Outlet Grounding			35.83	20.99%	35.83	21.0%				
PVC Venting					268.83	100%				
Conceal Venting					412.57	10.8%				
Condensate Disposal					86.00	25.6%				
HPWH Cost Adder									63.50	100%
Drain Pan Increase									1.90	100%
Space Constraints: Tempering					155.76	9.98%			144.60	10.9%
Space Constraints: Door Jamb					237.81	16.11%				
Space Constraints: Louvered Door									325.44	20.3%
Net Cost	$518.41		$1,349.42		$928.76		$314.85		$453.02	

In the case of a gas water heater, a stainless steel vent connector is required if the water heater installed has a recovery efficiency > 78% because the flue gas may condense. In the rulemaking, this cost is applied to 24% of the water heaters simulated here. Two factors influence the EF of the gas water heater: combustion efficiency and tank losses. It is possible to have units with the same EF but different combustion efficiencies (and recovery efficiencies) if tank losses vary. This leads to the vent connector being applied to only a certain percentage of installations. Two possible venting configurations are considered here. In cases where the water heater is co-located with a furnace (61% of homes), they share a common flue vent and the venting cost for the gas water heater is the incremental cost of attaching the water heater to the common vent. This includes the cost of a tee in the vent, a short length of ducting to connect the water heater to the tee, and a vent connector to connect the water heater to the vent. When a gas water heater is not co-located with a furnace (39% of homes), the water heater must have its own flue vent, which is reflected in the additional venting cost. The venting cost considered here is for a typical two-story home and does not include the cost of adding a decorative chimney (which may be done for aesthetic reasons). For the purposes of this study, all furnaces and water heaters are assumed to be natural draft (requiring a vertical flue vent).

For tankless water heaters, the basic installation cost used in the rulemaking already includes average venting costs. All condensing water heaters are side vented with their own PVC vents. A condensate filter is assumed in the rulemaking to be necessary in 25% of homes. HPWHs have an additional cost as they are more complicated than a typical electric storage water heater and therefore likely take longer to install. A larger drain pan is also assumed to be required as the HPWH has more tank insulation than a typical electric water heater and therefore has a larger diameter.

In retrofit cases, the installation cost specified in the rulemaking is often quite different than in new construction scenarios. For all retrofit cases, the unit being replaced is assumed to be either a gas or an electric storage water heater with minimum efficiency considered in the rulemaking. Basic installation is more expensive in all cases because the old water heater must be removed. Large tank and attic cost adders are applied in the same way to new construction and retrofit homes. These adders are twice as large in retrofit cases, as it is a bit harder to accommodate these scenarios when they are not planned as part of the home construction. For gas water heaters, the stainless steel vent connector adder is still applied to the same percentage of homes as in the new construction case, because the vent connector is necessary for all homes installing a water heater with this EF and a high recovery efficiency to prevent corrosion issues. In each new construction and retrofit case, the costs are randomly applied to a certain percentage of homes, depending on the likelihood that a specific cost adder is necessary.

For tankless water heaters, the basic installation cost used in the rulemaking includes potential home modifications such as upsizing the gas line or changing the venting to accommodate the unit. However, “extreme” situations where major retrofits are necessary to install the unit are not considered as they are cost prohibitive. The cost of adding an electric outlet is applied to some cases because tankless water heaters need electricity for freeze protection, ignition, controls, and venting fans; a typical natural draft gas water heater requires no electricity. The cost of adding an electrical outlet for the tankless water heater applies to all homes where the water heater is not co-located with a furnace. The furnace is assumed to require an outlet, so one will be available for the tankless water heater if it is installed in the same space. An additional cost is associated with grounding the outlet in a homes that requires a new outlet if it was built before 1960. These costs are assumed to be included in the basic installation costs in new construction cases and therefore are not applied.

As in new construction, 25% of condensing water heaters have an additional cost associated with condensate disposal. A condensing water heater also requires an electrical outlet and has this cost applied in the same way as for a tankless water heater. There are also cost adders for retrofit scenarios associated with fitting the units into the same spaces as the old water heaters. In new construction, a home is presumably designed so it does not have any of these space constraints and there are no space constraint cost adders. The strategies considered here for dealing with these space constraints are using a smaller unit with a higher temperature set point and a tempering valve or door modification to fit the unit in a utility closet where the old unit was installed. The tempering valve approach is assumed to be used in 20% of manufactured homes and 10% of single-family and multifamily homes. Although the higher set point temperature and lower surface area associated with this approach lead to similar tank losses, there are nonlinear efficiency impacts for using this approach with condensing water heaters and HPWHs. For these technologies, the efficiency is a function of tank temperature; increasing the tank temperature changes the efficiency. The cost of adding a tempering valve is included in the installation cost determination, but its efficiency impact is not modeled. The door modification strategy is applied to only 50% of manufactured homes and 25% of single-family and multifamily homes where the water heaters are installed indoors. These two strategies for dealing with space constraints are mutually exclusive; tempering valves take priority over door modifications. All condensing water heaters require a PVC side vent. In 25% of indoor installations, the rulemaking assumes an additional cost to conceal the new PVC venting.

As in new construction, a HPWH has a cost adder because it is more complex than an electric storage water heater; its larger diameter also leads to an additional drain pan cost. The HPWH may also encounter space constraints in a retrofit scenario, which may be dealt with by raising the set point and adding a tempering valve or a louvered door to the utility closet. The energy impact of the tempering valve may be significant because of reduced heat pump COP at higher tank temperatures. This is not modeled, although the cost is applied. In this case, the tempering valve strategy is used in 50% of manufactured homes and 20% of single-family and multifamily homes. The louvered door strategy, which should ensure sufficient airflow around the HPWH, is applied to 75% of installations in manufactured homes and 50% of indoor installations in single-family and multifamily homes. These two strategies are mutually exclusive; the louvered door approach is applied first. The rulemaking also considers the case of venting the HPWH to outdoor air as an alternative to a louvered door. However, this cost is not included here, as only some HPWHs on the market can be vented and a vented unit may have significantly different energy consumption than what is calculated in this study, which assumed a louvered door would be used in installations where the water heater is in conditioned space.

Appendix G Life Cycle Cost of All Water Heaters in Parametric Study

New Construction, No Incentives

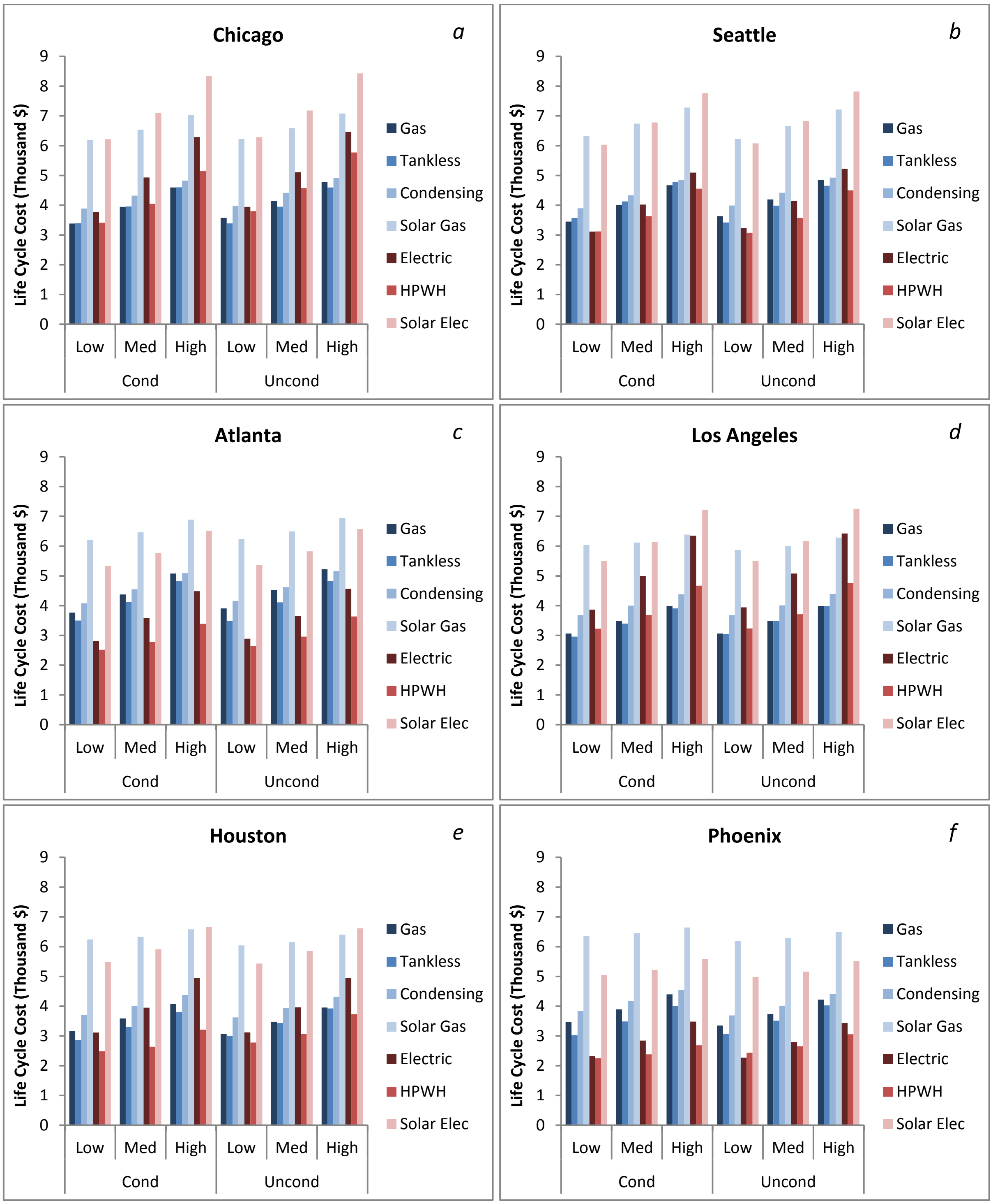

Figure 51a–f. LCC of all water heaters for new homes with no incentives

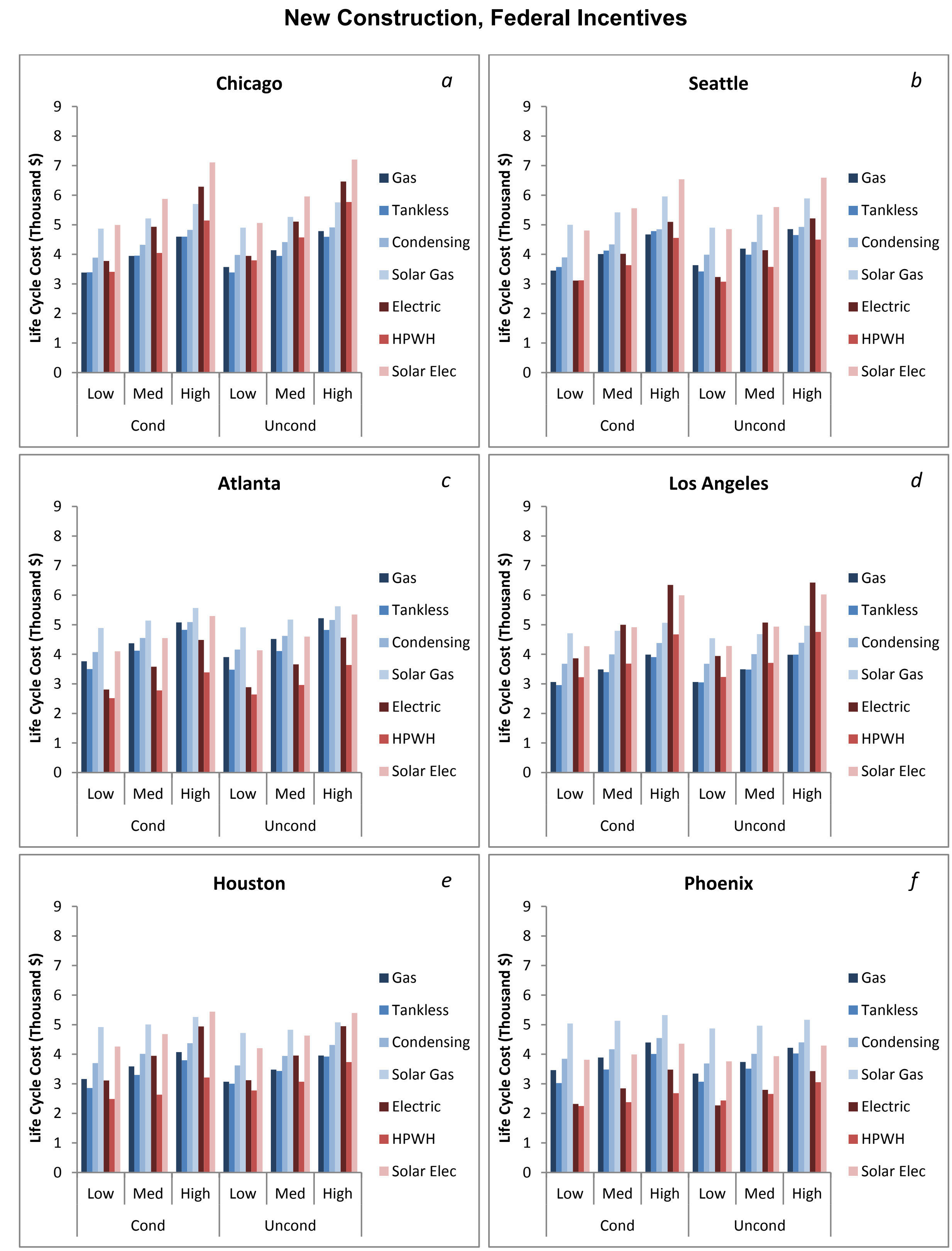

Figure 52a–f. LCC of all water heaters for new homes with federal incentives

New Construction, All Incentives

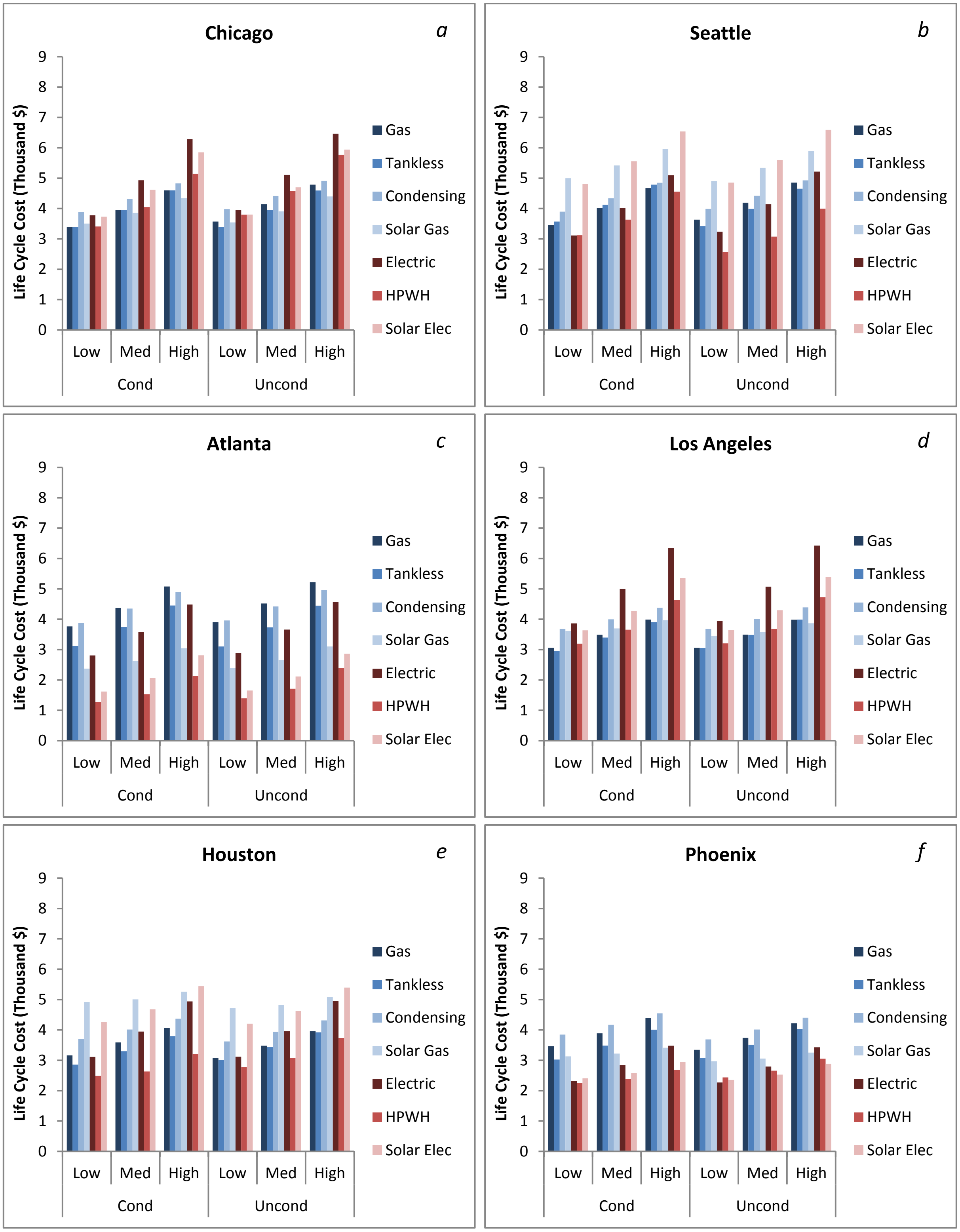

Figure 53a–f. LCC of all water heaters for new homes with all incentives

Retrofit, No Incentives

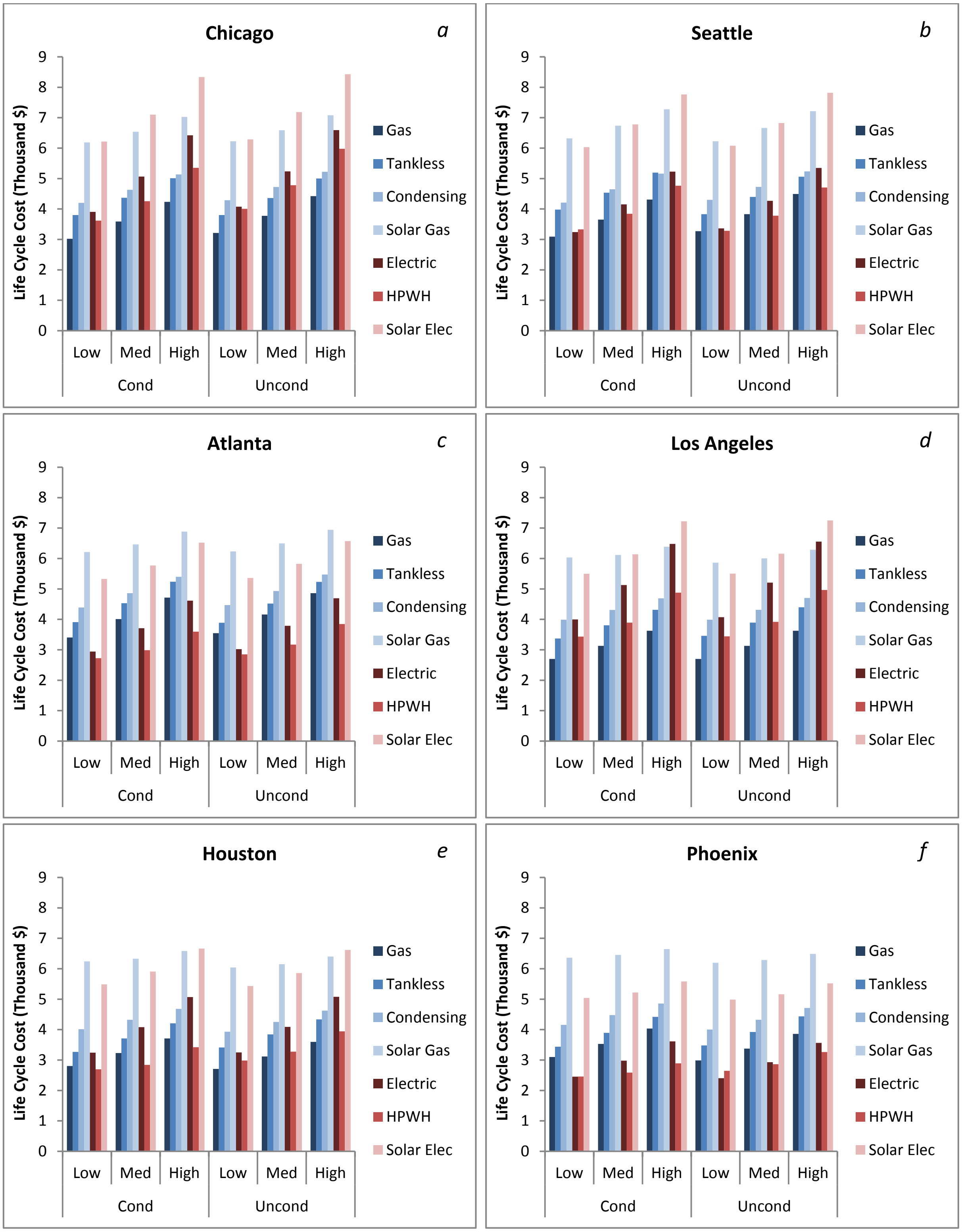

Figure 54a–f. LCC of all water heaters for retrofit homes with no incentives

Retrofit, Federal Incentives

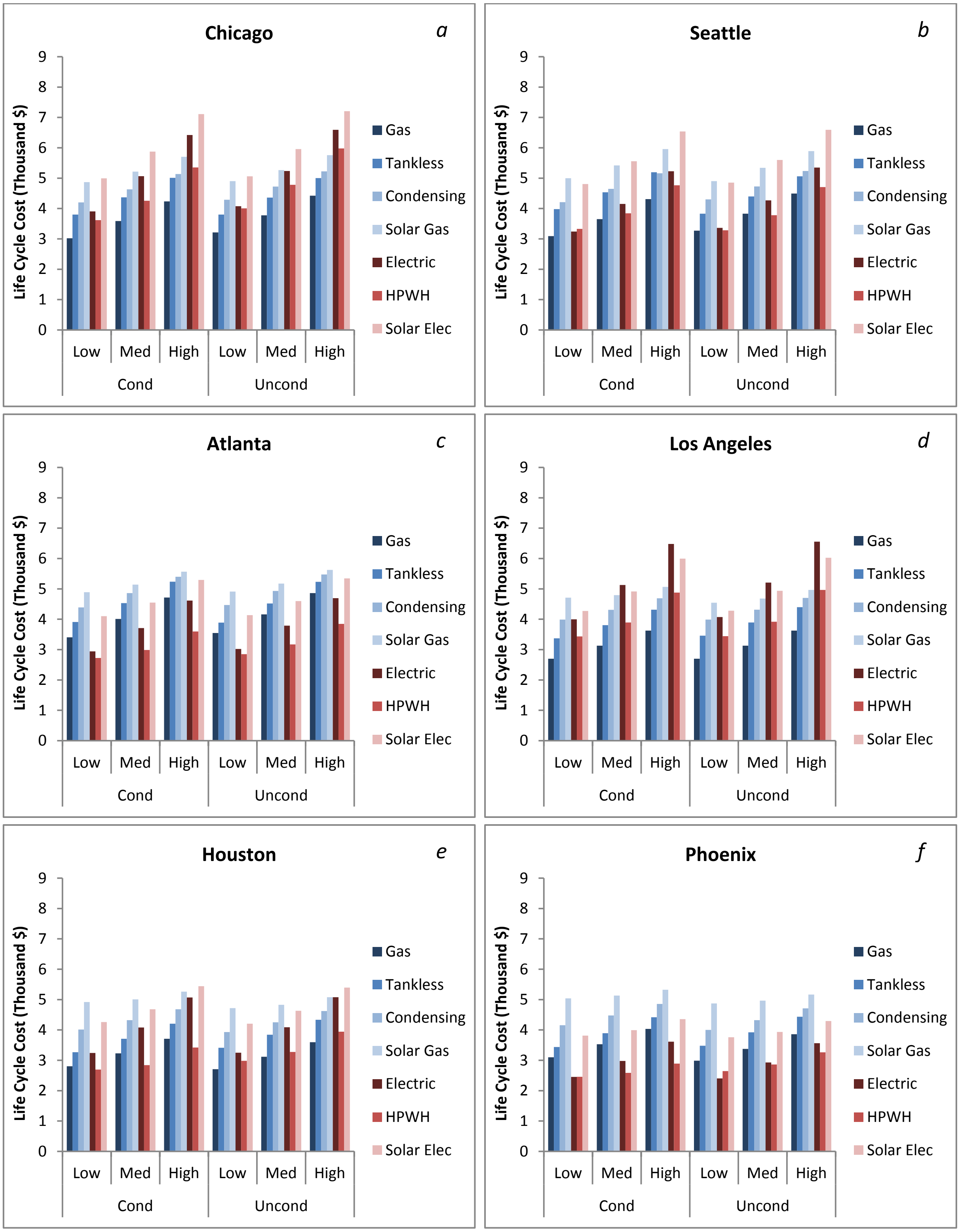

Figure 55a–f. LCC of all water heaters for retrofit homes with federal incentives

Retrofit, All Incentives

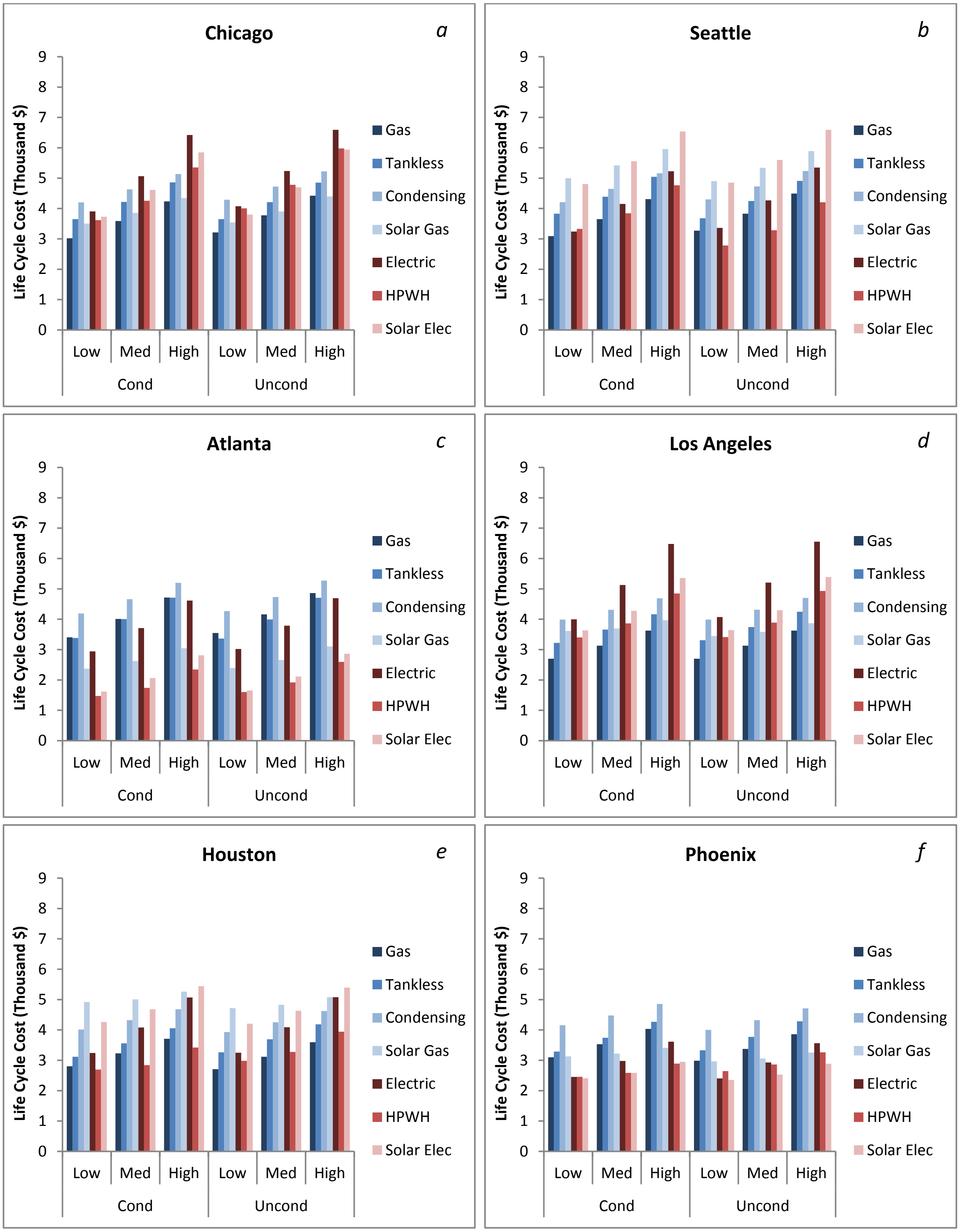

Figure 56a–f. LCC of all water heaters for retrofit homes with all incentives