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Lab Testing of Tankless Water Heater Systems

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The objective of this study was to inform the Northwest Energy Efficiency Alliance (NEEA) and its members regarding the current level of performance of tankless water heaters, their potential energy and cost savings, as well as reliability and safety.

In buildings, water heating is one of the largest uses of natural gas in the United States and is still mostly dominated by low efficiency, atmospherically vented, storage water heaters. Tankless water heaters, with higher minimum required efficiencies, have long been demonstrated to offer energy savings as high as 20-30%. However, due to their high installation cost compared to like-for-like replacement of non-condensing storage water heaters, the payback periods have not been adequate without significant incentives. A significant portion of the installation cost has been attributed to the need to upsize or install a new gas line to supply the high capacity burners of tankless products. Recent changes to the National Fuel Gas Code permit larger gas appliances to use ½" gas lines in certain situations. New tankless products have emerged touting ½" gas line capability and are marketed towards retrofit applications. During the same time, the water heating rating method has been revised to better account for energy use under realistic hot water draw patterns. With these recent changes encouraging reductions in installation costs and improved real-world performance, the economics of these products may have become more favorable.

A thorough laboratory evaluation was conducted of a sample of these products, most of which were donated by major tankless manufacturers. These products included popular models that are condensing, non-condensing, as well as low, medium, and high capacity. Testing included performance verification of the Uniform Energy Factor (UEF) in a minimally compliant installation according to the National Fuel Gas Code, as well as a stress test under adverse operating conditions simulating an improper installation that starved the water heater of gas pressure during operation. Additionally, a code review was conducted to determine under what circumstances existing ½" gas lines could be reused for tankless retrofits. The major findings and recommendations from this portion of the investigation are:

1. Tankless water heaters installed properly according to the National Fuel Gas Code will perform as designed and rated, even if minimally compliant.
2. In improper installations, if the tankless products are robbed of gas supply during operation, they may misfire and operate in an unstable manner.
3. Tankless products utilizing negative pressure gas valves are more tolerant of supply pressure drops below the minimum required by the manufacturer. However, improper installs with these products could cause problems for other gas appliances on the same distribution system.
4. Reusing ½" gas lines in retrofit applications is feasible using new National Fuel Gas Code provisions. A gas distribution system designed using National Fuel Gas Code is conservative by design and will usually result in excess capacity, which may be the case for many older homes.
5. There are several requirements and potential barriers for reusing existing gas lines, including:
    a. The capacity of the existing system must be accurately determined. This may not be possible if gas lines are hidden behind walls.

b. The gas supply pressure must be increased to at least 8 inWC by adjusting the gas regulator at the entry point of the building. Note, 7 inWC is the common setting throughout the United States.
c. The minimum gas pressure must be supplied to all other gas appliances and static gas pressure may not exceed the maximum specified by the manufacturers.

6. Further research into the reuse of ½" gas lines for tankless products should seek to answer the following questions:
   a. How frequently can the capacity of the gas distribution system be determined accurately?
   b. How frequently can the gas supply pressure be increased to at least 8 inWC?
   c. Are there any perceived barriers from installers to use the new provisions of the National Fuel Gas Code with respect to ½" gas lines?
   d. Would better tools for determining gas distribution system capacity enable more frequent reuse of existing gas lines?

Additional testing was conducted to determine performance characteristics that could be coupled with 8760-hour building energy models. Simulations of high, medium, and low hot water usage homes were performed for several locations in the Pacific Northwest and other locations around the United States. Energy and cost savings were estimated for condensing tankless, non-condensing tankless, and condensing storage water heaters when replacing a minimum efficiency storage water heater. Simple payback periods for different installations were calculated, summarized in Figure S2. The major findings from this portion of the investigation are:

1. Condensing tankless water heaters offer annual energy savings of 30-35% in all usage cases.
2. Energy savings translate to operating cost savings of $50-70 annually.
3. If gas lines must be upsized, the installed cost for tankless products results in simple payback of more than 25 years without incentives.
4. Simple payback periods reduce to less than 15 years if existing gas lines can be reused.
5. Operating cost savings can be wiped out entirely depending on the annual maintenance cost for tankless products, up to ~$150.

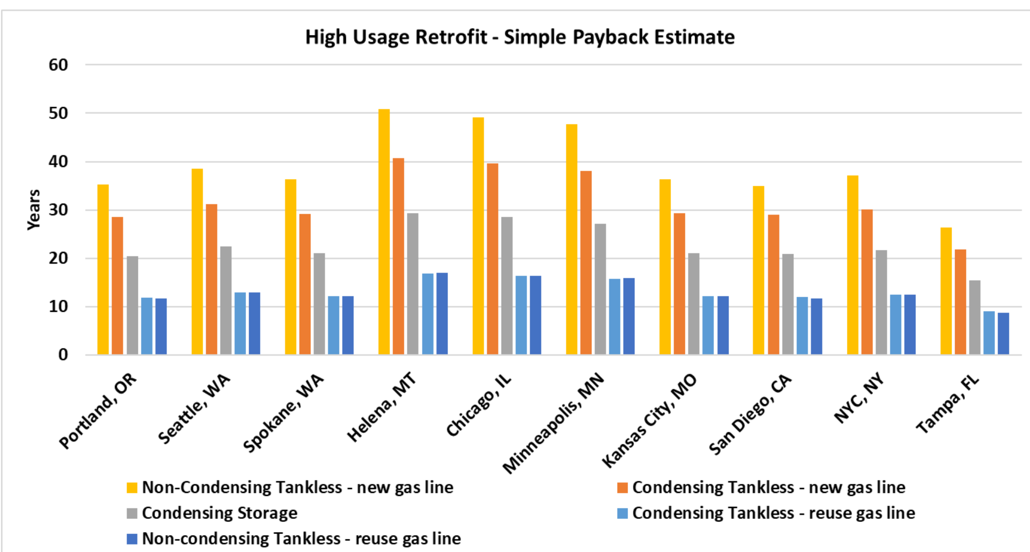

Figure S2. Estimated simple payback for tankless products using new performance data and installation costs relative to a minimum efficiency like-for-like replacement storage water heater

Background

Introduction

In buildings, water heating is one of the largest uses of natural gas in the United States. In residential applications, this market has been dominated by low efficiency, atmospherically vented, storage water heaters, many of which have rated Uniform Energy Factor (UEF) of 0.62 (current federal minimum) or lower for older models. Tankless water heaters have a federal minimum UEF of 0.81 and can exceed 0.9 for condensing. They have been demonstrated to offer significant energy savings over storage alternatives in numerous field and laboratory studies [1] [2] [3] [4]. While their popularity has been increasing at a steady pace, their adoption has been hampered by high installation costs and therefore lengthy payback periods in retrofit applications.

Tankless water heaters typically have firing rates in the 120-200 MBH range and in many applications will be the largest single gas appliance in a residence. In many retrofit applications, this has required upsizing or installing dedicated ¾"-1" gas lines that can handle the required gas flow with minimal pressure drop. In retrofits replacing atmospherically vented, storage water heaters, additional upgrades may be required for venting, along with having a larger gas meter, the addition of a nearby power outlet, and having a nearby drain for condensing water heaters. Installed costs for tankless water heaters in retrofit applications can exceed $3000, a ~$2000 incremental cost over a like-for-like replacement of a non-condensing storage water heater [4].

National Fuel Gas Code (NFPA 54 / ANSI Z223.1) is the nation's oldest model gas code. All installations of gas systems in the country must be compliant with NFPA 54 if no local code variations supersede. As of 2012, NFPA 54 has added new provisions to its gas pipe sizing methods that permit appliances with up to 200 MBH firing rates to use ½" Schedule-40 gas lines (most common in the US) up to 40 ft-equivalent. These new provisions open the possibility of reusing existing gas lines in retrofit applications, potentially reducing installation costs. During the same time, the federal method of testing and rating water heaters has been revised to the "Uniform Test Method for Measuring the Energy Consumption of Water Heaters" (10 CFR Appendix E to Subpart B of Part 4) which generates the Uniform Energy Factor (UEF) rating. This new rating supersedes the Energy Factor (EF) rating that has been shown to underestimate energy consumption of water heaters by 10% or more [4]. Since the rollout of these new code and rating changes, new tankless products have emerged that are marketed towards retrofit applications with features such as vertical water connections, venting with narrow diameter PVC piping, and being ½" gas line capable.

The purpose of this study was to help inform NEEA regarding these new products and their potential benefits. While eliminating the requirement for upsizing the gas line alone does not eliminate the increased installation cost, it may shift the economics of tankless water heaters towards more favorable payback periods. The specific research questions that this project sought to answer were:

1. What are these new ½" gas line capable products?
2. What are their operating characteristics and limitations when utilizing ½" gas lines?
3. What are the necessary conditions for eliminating the need for upsized gas lines?
4. Do the new products have improved energy savings potential?
5. Do the new products have reduced installation costs and therefore improved economics?

Methodology

The project was broken down into two tasks. As part of task one, a detailed laboratory evaluation of new tankless models was conducted in order to:

1. Validate their rated performance, as measured by the Uniform Energy Factor, while simulating conditions of an install using ½" gas lines.

2. Stress test the ½" gas line capable products under adverse gas operating condition to determine how the products react if installed improperly.
3. Gather detailed performance characteristics that can be used with building energy models to accurately predict real-world energy consumption.

A detailed description of the experimental apparatus and procedures is provided in Appendix A. Seven water heaters were tested in all, six of which were donated by the Original Equipment Manufacturers (OEMs), summarized in Table 1. Water heaters chosen for testing represent the "popular" models as indicated by the OEMs. All of the water heaters tested, except for one, were ½" gas line capable according to product literature for each model.

Table 1. Tankless water heaters evaluated in this study

	Gas Use (MBH)	**UEF Rated**	**Type**
Model A	180	0.82	Non-condensing, Medium Capacity
Model B	199	0.97	Condensing, High Capacity
Model C	120	0.96	Condensing, Low Capacity
Model D	199	0.93	Condensing, High Capacity
Model E	130	0.91	Condensing, Low Capacity
Model F	199	0.96	Condensing, High Capacity
Model G	180	0.95	Condensing, Medium Capacity

In task two, the performance data for each tested water heater was coupled with detailed 8760-hour energy simulations using BEopt [5] and EnergyPlus [6] to estimate annual energy consumption and potential savings compared to a non-condensing storage water heater. Simulations of tankless water heaters was based on the Lumped Heat Capacity model first developed at NREL [7] and expanded as part of this study. Appendix B provides a more detailed description of the model development and its capabilities. Combining the estimated energy savings with available installed cost data, payback periods were estimated for different climates and usage cases. Task two also included a relevant code review to determine requirements and limitations of reusing ½" gas lines with tankless water heaters.

Key Results

Requirements and Limitations for Using ½" Gas Lines

A code review was conducted to determine the requirements and limitations of using ½" gas lines with tankless water heaters up to 200 MBH. The code review included NFPA 54 – National Fuel Gas Code, ANSI Z21.10.3 – standard to which tankless products are built, as well as a review of any local code variations in the Pacific Northwest. Main findings of this code review are:

- ANSI Z21.10.3 has no provisions regarding gas line size to be supplied to the water heater. It does require that the units are tested at their normal as well as reduced pressures (3.5 inWC). No requirements for gas shut off systems or safety features are specified in the case of insufficient or excessive gas pressures. Only a high water temperature automatic gas shut off system is required for water heaters. A more detailed review of ANSI Z21.10.3 is provided in Appendix C.
- International Fuel Gas Code (IFGC) has been adopted as the model fuel gas code in Oregon, Washington, Montana, and Idaho. IFGC and NFPA 54 are harmonized with respect gas pipe sizing requirements.
- No local code variations were found in the major metro areas of PNW, including Portland, Seattle, Boise, and Spokane. The same gas line sizing tables are included in local codes as are found in NFPA 54.
- NFPA 54 outlines several procedures for adequately sizing a gas pipe system for a building. A more detailed summary of the procedures is provided in Appendix C. Any of the methods can be used for sizing the gas lines.

The provisions in recent versions of NFPA 54 that permit larger gas appliances to be used with ½" gas lines are the addition of new pipe capacity tables, examples of which are provided in Appendix C. These tables specify the maximum capacity in cubic feet per hour of a given length and diameter of pipe and a prescribed pressure drop. Permitted pressure drops historically have been 0.3 and 0.5 inWC. New versions of NFPA 54 permit larger pressure drops including 3 in WC and higher. As long the system has enough capacity and minimum and maximum pressures are not exceeded, any of the tables can be used for sizing. How these changes permit ½" gas lines to be reused is best illustrated with an example.

Figure 1 is a typical schematic of a gas distribution system of a home that may be used in a sizing calculation. The Longest Length Method is the most commonly used approach for sizing gas lines. It is easy to use, fast, and results in conservative capacity estimates. This approach assumes that each branch of the distribution system has the same length as the longest branch, and gas pipe sizes are determined for each segment using actual branch demand. The gas distribution system depicted in Figure 1 for an older home would have been sized using the Longest Length Method and pipe capacity charts for 0.3 or 0.5 inWC pressure drop. Results of this sizing exercise are summarized in Table 1.

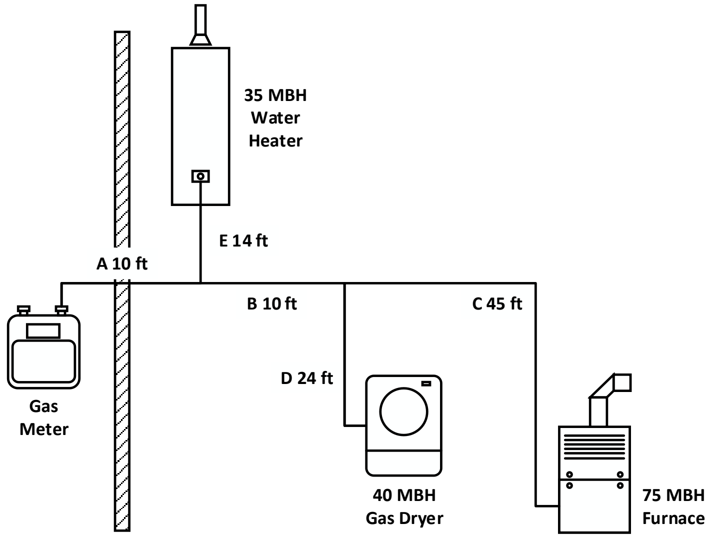

Figure 1. Example gas line sizing diagram

Table 2. Example Schedule-40 metallic gas line sizing results according to NFPA 54

	Longest Length Method			Branch Length Method
Line Segment	**0.5 inWC ΔP Size[1]**	**0.5 inWC ΔP Capacity (MBH)[1]**	**3 inWC ΔP Capacity (MBH)[2]**	**3 inWC ΔP Capacity (MBH)[2]**
A	1”	237	624	624
B	1”	237	624	624
C	¾”	126	331	331
D	½”	60	158	190
E	½”	60	158	250
[1]Minimum required gas supply pressure at the meter of 5.5 inWC [2]Minimum required gas supply pressure at the meter of 8 inWC				

Based on the Longest Length Method and 0.5 inWC pressure drop, the branch with the storage water heater (Segment E) has enough capacity up to 60 MBH while the whole distribution system can only accommodate 237 MBH. Without new sizing tables in NFPA 54, a new gas line would have to be run for the tankless. However, using the 3 inWC pressure drop table in the newer versions of NFPA 54, the gas distribution system has enough capacity for up 624 MBH, and up to 158 MBH on the water heater branch. To use this sizing table, the gas supply pressure at the meter would have to be increased to at least 8 inWC, where’s 7 inWC is typical in most US residences.

An alternate sizing method described in NFPA 54 is the Branch Length Method, which is less conservative than the Longest Length Method. It uses actual length from the meter to the appliances as well as its firing capacity to size the side branches. Using the Branch Length Method, the capacity of Segment E in Figure 1 is up to 250 MBH. In this way, existing gas lines could be reused for larger appliances. However, some potential barriers to doing this in retrofit applications are:

- Inability to accurately map the existing gas lines and to determine the systems’ capacity. If the gas lines are behind walls, it may not be possible to get exact lengths and diameters of all segments.
- Inability or reluctance of installers to raise the gas pressure at the meter to at least 8 inWC.
- Installers typically prefer to be conservative and avoid callbacks. Improperly sized gas lines could result in equipment faults and unsafe operation. Therefore, they may be reluctant to use less conservative sizing methods.

An additional concern has been expressed historically by gas utilities with regards to a possible gas surge that could be caused by a high capacity tankless water turning on. The typical concerns are around reduction of capacity at the street level gas distribution system and false closures of excess flow valves. Prior research by Minnesota Center for Energy and the Environment [4] did not indicate a significant change in peak gas demand, and modern gas distribution system operate at high pressures and can handle high capacities. False closure of excess flow valves (safety shutoffs) are unlikely as typically they are designed to close at flows of ≥400 MBH.

Performance Verification of Tankless Products

The performance verification of tankless products was conducted in two parts. First, their rated UEF, as determined by "Uniform Test Method for Measuring the Energy Consumption of Water Heaters" (10 CFR Appendix E to Subpart B of Part 4), was validated using 24-hour simulated use tests. If ½" gas lines are reused in a retrofit, the tankless product may be installed such that it operates near the minimum required pressure at maximum fire. This represents a minimally NFPA 54 compliant installation. These tests were conducted by setting the static gas supply pressure at the water heater to the minimum required while at 100% firing rate (3.5-4 inWC for all models tested). The 24-hour test was then conducted according to the DOE procedure and a UEF value calculated. The measured UEF values are compared to the rated values in Table 3.

Table 3. Measured and rated UEF values

	UEF Measured[1]	**UEF Rated[2]**
Model A	0.87	0.82
Model B	0.97	0.97
Model C	0.97	0.96
Model D	0.96	0.93
Model E	0.96	0.91
Model F	0.96	0.96
Model G	0.95	0.95

[1]Estimated uncertainty of ±0.015 UEF
[2]According to AHRI Directory of Certified Product Performance

All measured UEF values were at or near those reported for each water heater. Other measured parameters such as max gpm and recovery efficiency are summarized in Appendix D. During the 24-hour UEF tests, the maximum draw rate is only 3 gpm. For high capacity water heaters, maximum firing rate would not be achieved unless at maximum gpm (4.5-5.5 gpm). During the 24-hour tests, these water heaters were modulating their burners down and gas pressure at the inlet was above 6 inWC for all draws. The smaller capacity water heaters will operate near maximum fire at 3 gpm. To confirm that these units would operate properly near minimum required gas pressure, Model E was run through a second 24-hour UEF test again using the high usage draw pattern. Its calculated UEF was identical to the one listed in Table 3. The primary conclusion from these results is:

- If the tankless water heaters are installed properly, according to NFPA 54, they will operate as expected, regardless of the gas line size.

In the second part, a portion of the water heaters were subjected to a stress test under adverse gas pressure operating conditions, simulating an improper install. This could occur if an installer incorrectly determines the capacity of the existing gas distribution system. The worst-case scenario for an improper install is the water heater operating at 100% firing rate and experiencing a reduction in gas supply pressure, which may occur when another large appliance is turned on. For these tests, the water heaters were brought up to maximum firing rate, allowed to come to steady state, and then the gas pressure was slowly reduced. The emissions of carbon monoxide (CO) were used as an indicator of misfiring. The results of these tests for two models are compared in Figure 2.

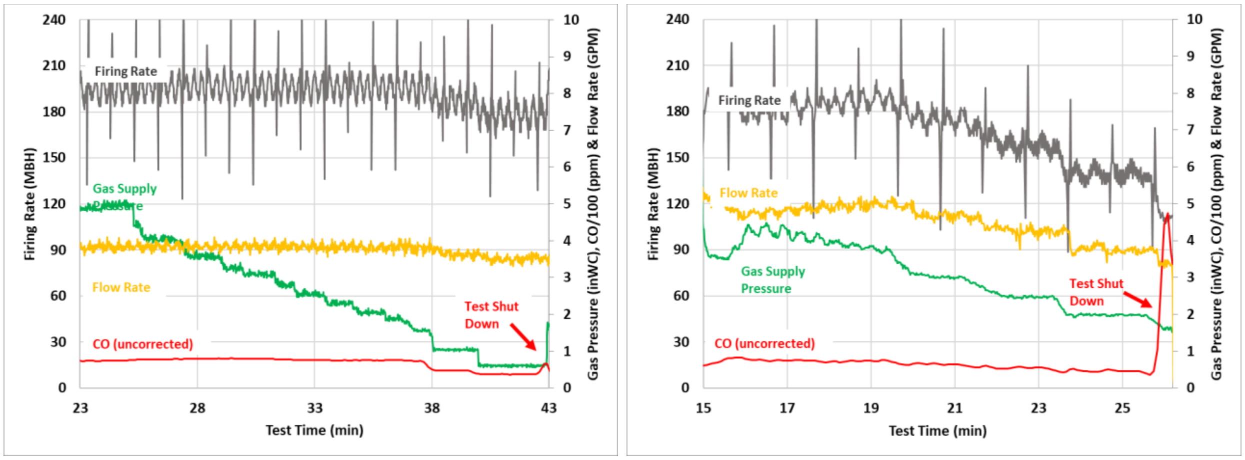

Figure 2. Stress test results example, negative pressure gas valve (left) and positive pressure gas valve (right)

Some of the water heaters were able to operate in a stable manner without the firing rate dropping or emission of CO spiking for gas supply pressure down to 2 inWC. Below 2 inWC, the water heaters partly restricted the flow of hot water and the firing rates were reduced. The tests were terminated when the stoichiometry of combustion began changing significantly. However, no unstable operation was observed at pressure less than 1 inWC. Other models began adjusting the flow of hot water and modulating down almost as soon at the gas supply pressure began to drop. The test was terminated when the water heaters began to hum, vibrate, and the emission of CO spiked more than 400 ppm. This condition was indicative misfiring.

The distinguishing feature between the water heaters that operated unstably at low pressure and those that did not is the type of gas valve used. The water heaters that were stable use a negative pressure gas valve, the others use a positive pressure gas valve. The difference in operation is that negative pressure gas valves can "suck" gas from the supply line, and therefore are less sensitive to the gas supply pressure. The primary findings and recommendations from the stress tests are:

- Water heaters using positive pressure gas valves are sensitive to gas supply pressure and may operate improperly if the pressure dips below the minimum required.
- Tankless water heaters using negative pressure gas valves are less sensitive to supply pressure and will likely continue to operate at pressure below the minimum required.
- Tankless water heaters using negative pressure gas valves in improper installs may pose a problem for other gas appliances that use positive pressure gas valves.
- None of the water heaters tested shut down on their own during the stress tests. Their safety and reliability could be improved by adding a capability to detect low supply pressure during operation and shutting down the burner.

Energy Savings and Economic Assessment of Tankless Products

To accurately predict the energy consumption of water heaters in the real world, more than just the UEF is needed [4]. 8760-hour building simulations were performed using realistic domestic how water (DHW) draw patterns, in different climates and use cases. A custom model was developed for tankless water heaters based on the Lumped Heat Capacity (LHC) model developed at NREL [7]. This model was combined with DHW loads generated by BEopt [5] and EnergyPlus [6]. Additional experiments were performed with each water heater to infer thermodynamic parameters for use with the LHC model, including the thermal capacitance, steady state efficiency, and standby loss coefficient. A more detailed description of the model development is provided in Appendix B.

Four locations were considered in the Pacific Northwest, including Portland, Seattle, Spokane, and Helena. Six additional cases were considered around the country for comparison. Three different use cases were investigated, high, medium, and low which approximate homes that are 4 bed 3-bath, 3 bed - 2 bath, and 2 bed – 1 bath. Four water heating options were simulated including a minimum efficiency 0.62 UEF non-condensing storage, a 0.82 UEF non-condensing tankless, 0.96 UEF condensing tankless, and for additional comparison a 0.82 UEF condensing storage water heater. The last option represents an alternative high-efficiency water heater choice that could yield energy savings on a similar order of magnitude but at potentially reduced installed costs. It was included in this study for comparison as an intermediate option. The annual gas consumption for each option in the high usage case is compared in Figure 3. All other use cases are plotted in Appendix E.

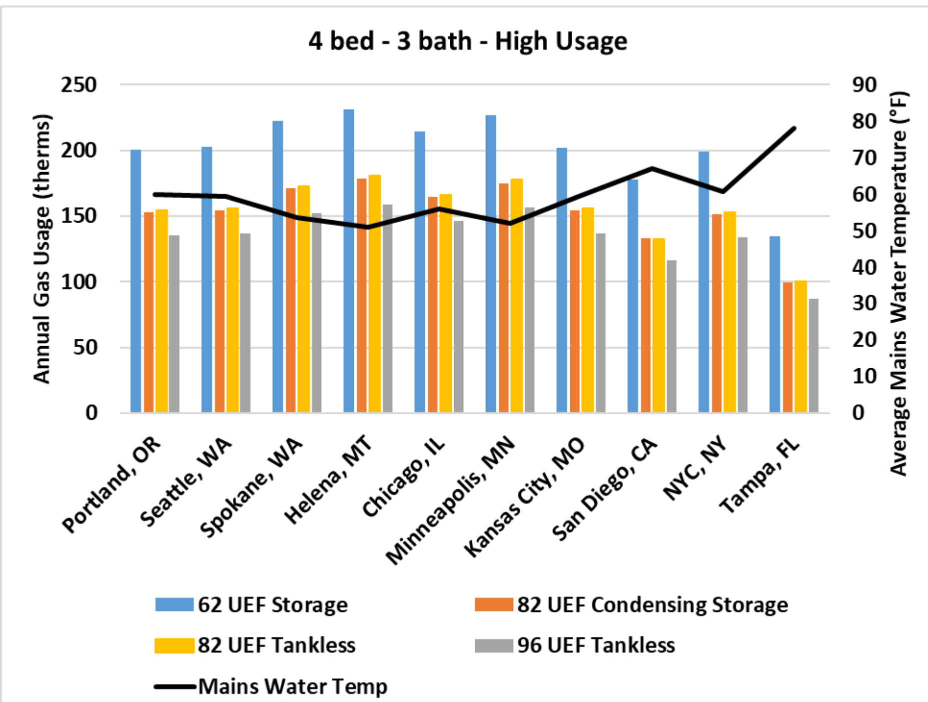

Figure 3. Annual gas consumption for all water heater options considered.

Water heater energy consumption is strongly correlated with average annual mains water temperature, despite the same draw patterns being used. More DHW was needed to temper mains supply in colder climates. With respect to energy savings, the condensing tankless offered the greatest average savings of 33%, while the non-condensing tankless and condensing storage both offered approximately 23% energy savings compared to the 0.62 UEF baseline. The relative savings were independent of the climate, but varied with use cases, summarized in Figure 4.

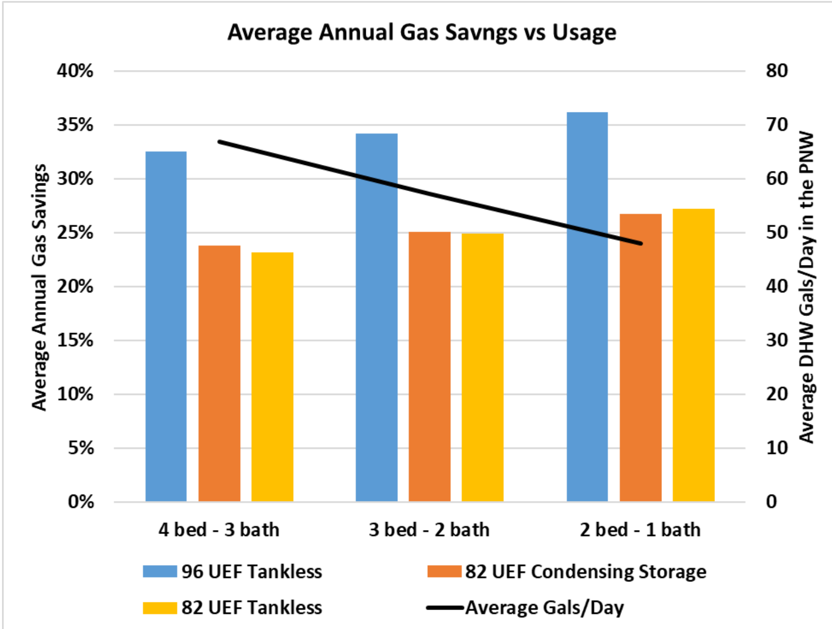

Figure 4. Relative energy savings for different use cases

Relative savings are higher for lower use cases due to increased penalty of standby heat losses of the 0.62 UEF storage water heater. These results are based on installations inside the conditioned space. If installed inside unconditioned space such as a garage, the savings for all high efficiency water heaters were approximately 2% higher. No other usage pattern changes were considered. While it has been suggested by at least one of the OEMs that switching to a tankless would increase the use of hot water, available research does not support this conclusion. A field trial conducted by Minnesota Center for Energy and Environment did not find a consistent increase in hot water usage on a daily basis [4]. The same study only showed a decrease the number of small volume draws and an increase in larger volume draws (>5 gal). Using the 2016 state average natural gas prices from Energy Information Administration, the annual operating cost savings for each high efficiency water heater are compared in Figure 5.

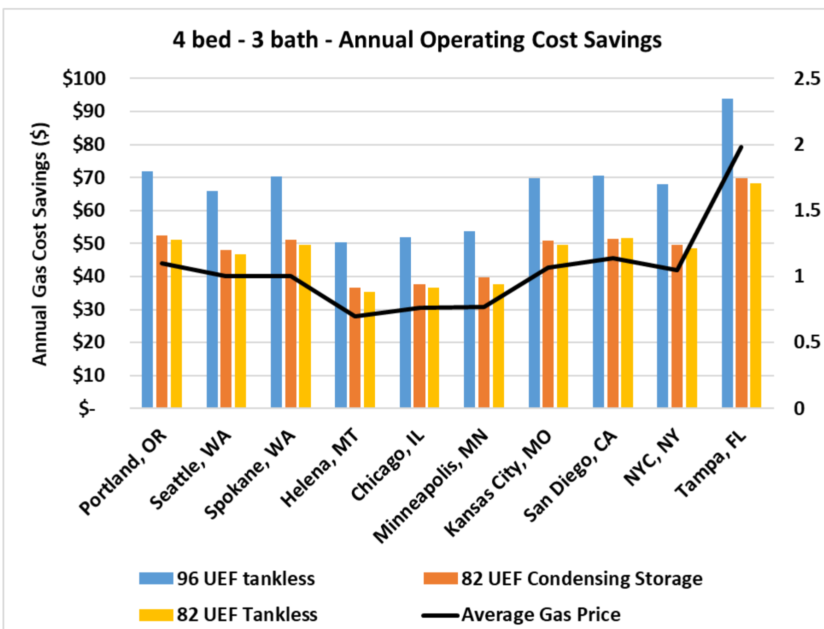

Figure 5. Annual operating cost savings

For the 2 bed – 1 bath case, the cost savings are lower by $5-10/year than those plotted in Figure 5. The increased cost of electricity is not included in these results but is expected to be marginal. These results do not include the annual maintenance for each water heater. Storage water heaters typically need sediment to be flushed out annually, while tankless water heaters need to be descaled every 1-5 years, depending on the hardness of the water. Costs of these procedures are ~$80 for storage water heater and ~$150 for the tankless based on a web search. While both can be performed by the resident, if a technician is called to perform these services on an annual basis, all operating cost savings will be wiped out. Table 4 summarizes estimated installed cost breakdown for condensing and non-condensing tankless water heaters, provided for this project by Energy 350, LLC (www.energy350.com) and Northwest Power and Conservation Council (www.nwcouncil.org).

Table 4. Installed cost assumptions used in the present analysis

0.62 UEF Baseline Like-for-like Replacement		
Installed Cost	$1,000	
Tankless Water Heater Retrofit		
	Condensing 0.96 UEF	Non-Condensing 0.82 UEF
Unit Cost[1]	$1,050	$750
Gas Line Extension	$ 1,200	
Plumber Labor	$400	
Plumbing Fittings	$50	
Electrician Labor	$200	
Condensate Management	$100	
Venting	$50	$100
Installed Cost – New Gas Line	$3,050	$2,800
Installed Cost – Reuse Gas Line	$1,850	$1,600
$ Incremental cost relative to baseline - New Gas Line	$2,050	$1,800
$ Incremental cost relative to baseline - Reuse Gas Line	$850	$600
[1]For comparison, the average cost of tankless products tested in this study is $1229 for condensing and $898 for non-condensing, using retail prices available online		

In a traditional install with a gas line upgrade, the installed costs are approximately $3050 for condensing and $2800 non-condensing tankless, a $2050 and $1800 incremental cost, respectively. If the existing gas line can be reused, the incremental costs are reduced to $850 and $600, respectively. Considering no incentives, the estimated simple payback periods for each retrofit are summarized in Figure 6.

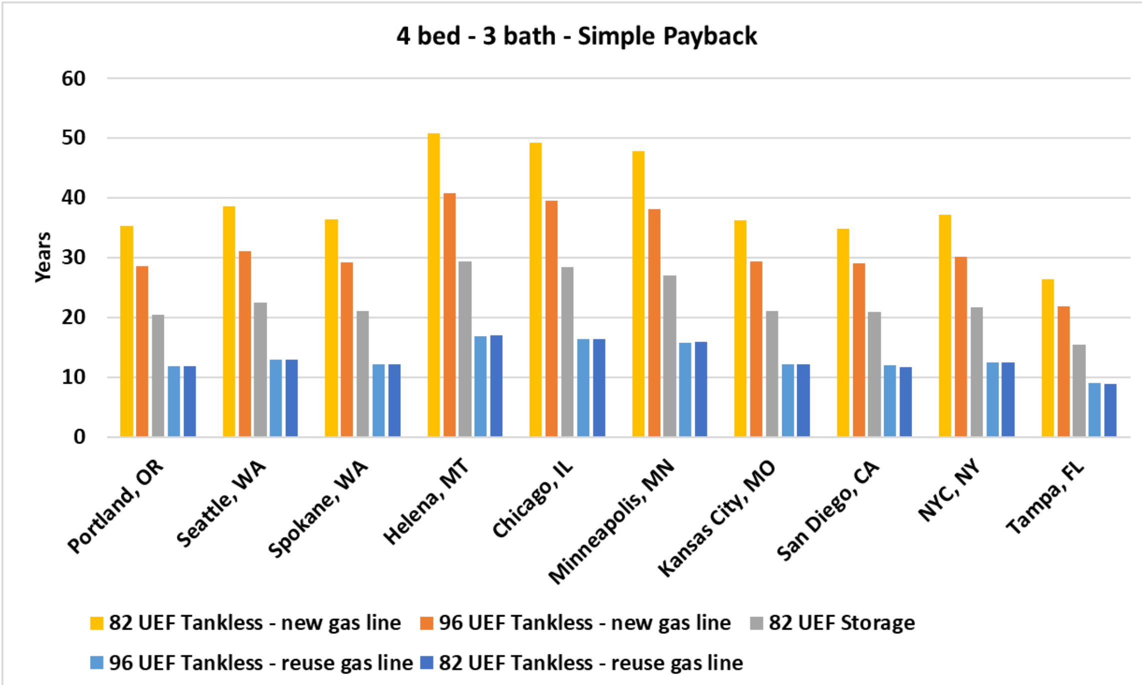

Figure 6. Estimated simple payback for tankless and condensing storage retrofit scenarios

In a retrofit where the gas line is still upsized, the payback periods are greater than the expected life of the tankless water heaters (~20 years). In a 2 bed – 1 bath use case, the payback periods are approximately 5-8 years longer than those in Figure 6. However, if the existing gas lines can be reused, the payback periods reduce to less than 15 years in most locations. With a ~$300 incentive, the payback periods can be lowered to less than 10 years.

The primary findings of this portion of the investigation are:

- Tankless water heaters still offer significant energy savings over non-condensing storage water heaters. Replacing just 1% of the low-efficiency models with condensing tankless, ~15,000 units according to NEEA Residential Building Stock Assessment 2017, can equate to ~900,000 or more annual gas therm savings in the Pacific Northwest.
- The economics of tankless products in retrofits are similar to what was reported in prior studies if the gas line must be upsized. If the existing gas lines are reused, and with a modest incentive of $300, the simple payback periods can be reduced to less than 10 years. However, annual maintenance costs of tankless water heaters, up to ~$150, can wipe out operating cost savings and fully upset the economics.

Additional Findings

Predicting Tankless Water Heater Energy Consumption

The previous section and Appendix B describe the approach utilized in the present study to simulate tankless water heaters and predict their real-world energy consumption. While the LHC model is less complex than other approaches, e.g., [8], it can still be impractical since it requires numerical integration. Frequently, only the EF rating is used to estimate energy consumption and relative savings. Prior studies have shown that energy consumption estimates based on the EF rating can be underestimated by 10% or more, with worse results being seen for storage water heaters. The Uniform Energy Factor (UEF) evolved from the EF rating and attempts to better account for real world water heater performance by implementing realistic draw patterns with typical usage of 84, 55, 38, and 10 gal/day. However, it was found as part this study that the draw patterns utilized in the UEF test may still not be representative of real-world performance. Figure 7 plots the predictions of the LHC model of the present study for the different UEF draw patterns.

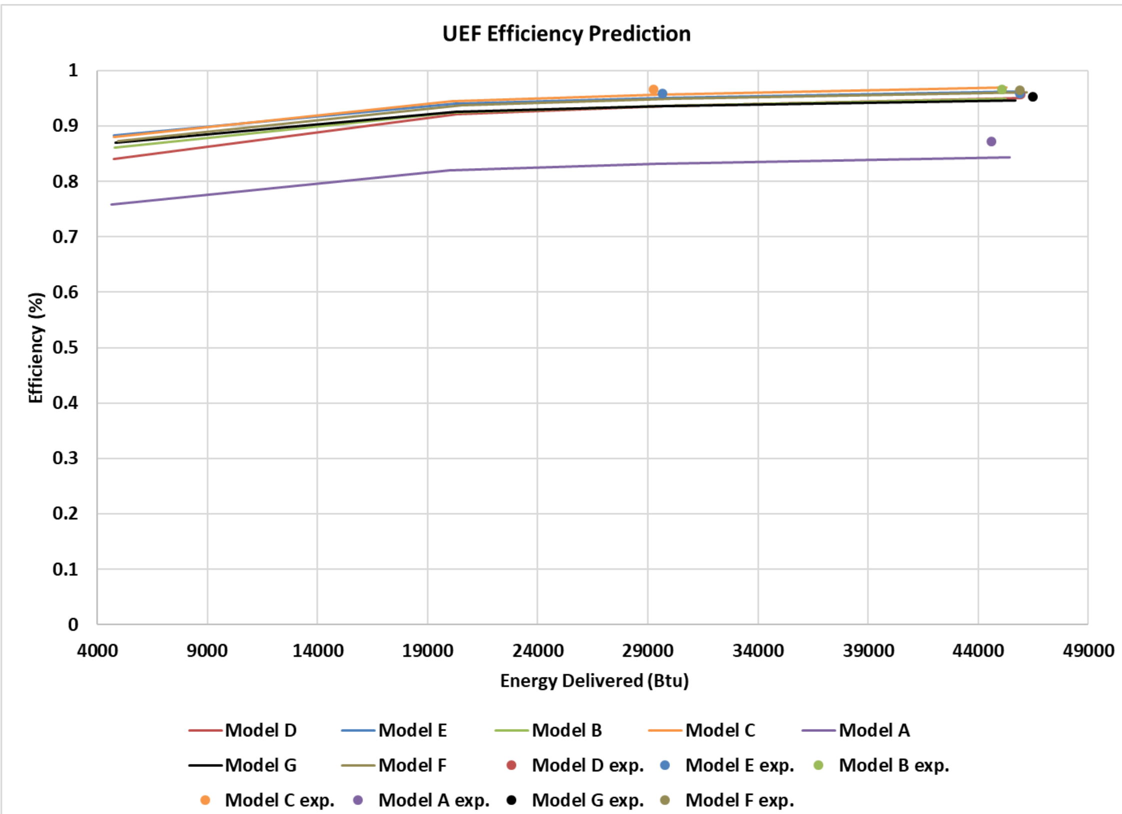

Figure 7. Simulated UEF tests using the LHC model compared to experimental measurements

Simulations of the UEF tests suggest that tankless water heaters would only experience an 8-9% decrease in performance in the lowest usage cases. However, real-world performance of tankless water heaters in very low usage cases has been documented to be as much as 20% lower than the rating. Figure 8 compares LHC model predictions to real world performance data collected as part of a study by Minnesota Center of Energy and Environment (MN CEE) [4].

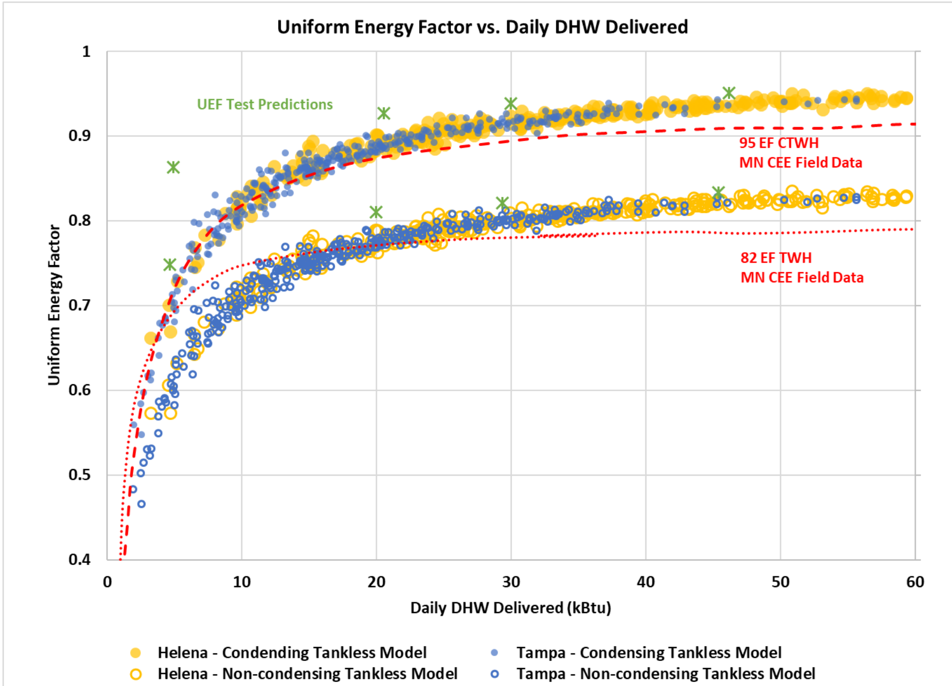

Figure 8. Predicted energy efficiency compared to available field measurement correlations from [4]

The LHC model is in good agreement with the field data correlations and shows a rapid decline in efficiency during low use days. In contrast, the UEF rating would underpredict energy consumption on these days by 25% or more. These results indicate a deficiency that is still present in the UEF rating.

An alternative simple method for estimating daily energy consumption is to use an input-output correlation developed from experimental data and simulations [4]. These correlations can accurately reproduce the data such as plotted in Figure 8. Using the LHC simulation results from this study, new correlations curves were developed for the 0.96 UEF and 0.82 UEF tankless water heaters. These correlations are provided in Figure 9.

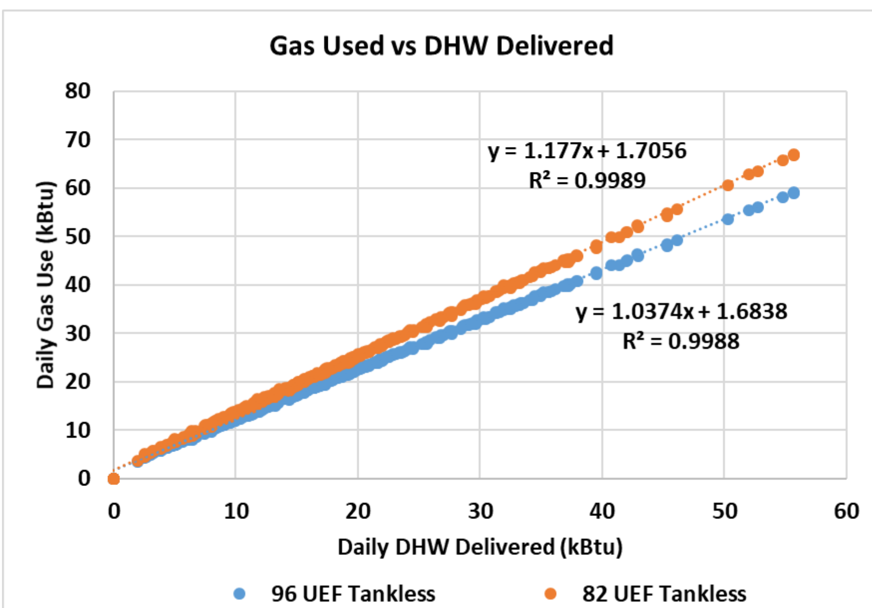

Figure 9. Input-output correlations to predict gas use for tankless products

References

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Appendix A – Experimental Methods

24-Hour Uniform Energy Factor Tests

UEF tests were conducted according to the DOE "Uniform Test Method for Measuring the Energy Consumption of Water Heaters" (10 CFR Appendix E to Subpart B of Part 4). It should be noted that GTI is not a certification laboratory. Best efforts were made to follow the UEF test procedure as closely as possible. A Schematic of the test apparatus utilized is provided in Figure 10.

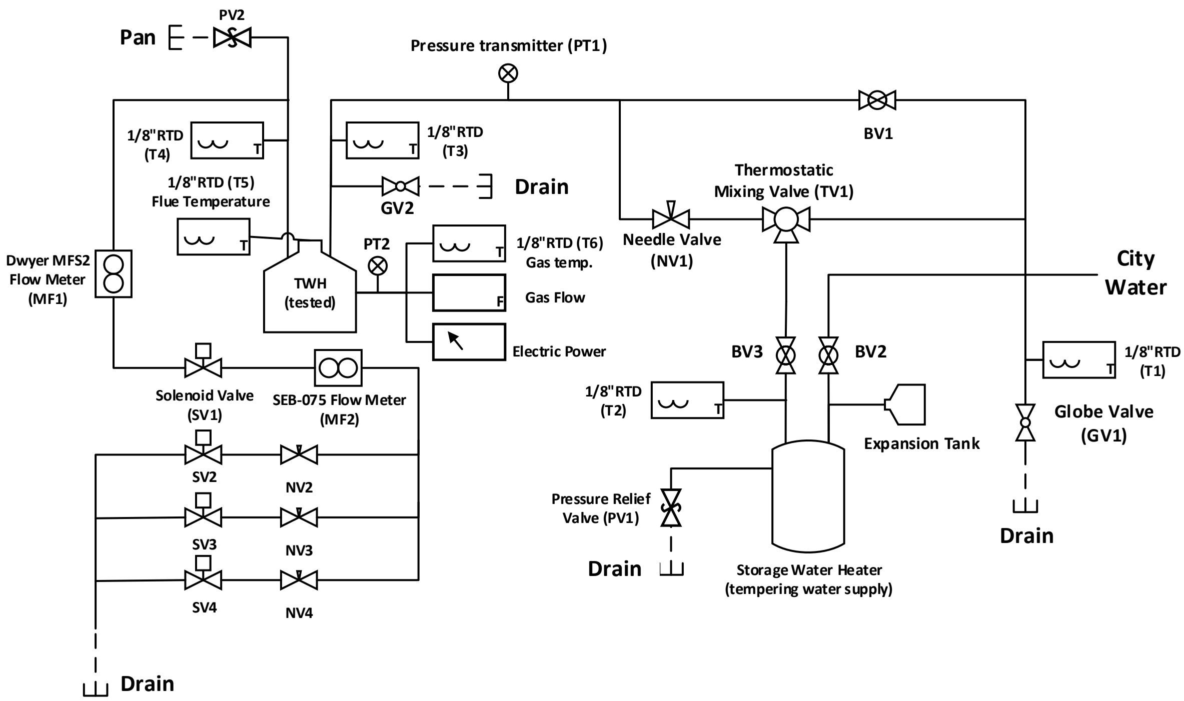

Figure 10. Process and instrumentation diagram of the test apparatus

Table 5 and Table 6 summarize the experimental instrumentation used during this investigation. Where relevant, equipment out of spec with the DOE test is identified.

Table 5. Instrumentation used and comparison of required and used actual accuracy

Measurement Point	Instrument Used	Required Accuracy	Instrument Accuracy
Gas pressure[1]	Dwyer ISDP-008	± 0.1 inWC	± 0.125 inWC
Gas temperature	Omega PRTF-10-2-100-1/8-6-E	N/A	Class B (less than +/-1.1 F at 140F, less than +/-0.63F at 50F)
Flue gas temperature	Omega PRTF-10-2-100-1/8-6-E	N/A	Class B (less than +/-1.1 F at 140F, less than +/-0.63F at 50F)
Atmospheric pressure[1]	Traceable Excursion-Trac Barometer	± 0.1 in. Hg	± 0.12 in. Hg
Water pressure	Ashcroft G2	± 1 psi	± 1% span (± 1 psi)
Air dry bulb temperature[1]	Omega HX15	± 0.2°F	± 1°F
Relative humidity[1]	Omega HX15	± 1.5% RH	± 2%
Inlet and outlet water temperatures	Omega P-M-1/10-1/8-6-0-P-3	± 0.2°F	1/10 DIN (less than ±0.15°F at 140F, less than ±0.08F at 50°F)
Water flow rate	Dwyer MFS2-2	± 1% of reading	± 1% of reading
Electricity use[1]	CCS WNB-3Y-208 and CTS-0750-015	± 0.5% of reading	± 1% (10 to 130% rated current)
Gas use	Elster DTM-200A	± 1% of reading	± 0.002 cu-ft
[1]Accuracy out of spec with DOE Uniform Energy Factor test			

Table 6. Flue gas analyzers use in the present study

Analyzers	CO Calibration Range (ppm)	NOx Calibration Range (ppm)	Heaters Tested
Horiba PG-350	0 - 800	0 - 79.1	Model B, Model E
Rosemount X-Stream	N/A	0 - 78.3	Model A, Model C, Model D, Model F, Model G
Eco Physics CLD 700 EL	0 - 400	N/A	

The 24-hour UEF tests were conducted according to the following procedure:

1. A maximum GPM test was completed an hour before each 24-hour UEF test for each tankless water heater. The water temperature setting on the water heater was set to 125°F and the water flow rate was gradually increased until a steady maximum value was reached.
2. The supplied gas pressure to the water heater was then adjusted to at least the minimum specified by the manufacturer (typically 3.5 or 4 inWC.) but no higher than 0.5 inWC over the rated minimum while the water heater was in operation at the maximum allowable water flow rate. This was done to simulate a "minimally" compliant NFPA 54 installation.
3. Once the gas pressure was adjusted, the water heater remained in operation at the maximum allowable flow rate for 10 minutes at which point the maximum GPM test was shut down.
4. After one hour, the 24-hour simulated use test was started. The test is fully automated using custom developed software. Gas pressure and water flow rate settings were not adjusted during that time.

5. A house gas analysis was performed on the day of each 24-hour UEF test to obtain an updated gas heating value. The heating value used in the UEF calculations was corrected for actual temperature and pressure seen at the gas meter.
6. Data during the test was recorded in 1-second intervals using custom data acquisition software and National Instruments hardware, summarized in Table 7.

Table 7. Data acquisition hardware used in the present study

Data Acquisition Hardware	
Input Modules	**Connector Blocks**
NI CFP-2000	N/A - Controller
NI CFP-AI-110	NI cFP-CB-3
NI CFP-CTR-502	NI cFP-CB-3
NI CFP-RTD-122	NI cFP-CB-3
NI CFP-RLY-421	NI cFP-CB-3
NI CFP-RTD-124	NI cFP-CB-3

The stress tests were conducted according to the following procedure:

1. The water heater was set to 125°F and flow rate adjusted until the maximum firing rate was achieved, per name plate.
2. The gas supply pressure at the water heater was adjusted close to the minimum required and the water heater allowed to operate for several minutes to reach steady state.
3. Gas pressure was then slowly lowered in increments of 0.5 inWC and the water heater allowed to operate at that pressure to achieve a steady state, 2-3 minutes.
4. Gas pressure was lowered again until one of two things occurred:
    a. Emissions of CO increased to greater than 400 ppm and the water heater began audibly humming and vibrating, indicative of a misfiring system.
    b. Gas pressure of 0.5-1 inWC was reached
5. The test was terminated when one of the above criteria was met.

Appendix D summarizes additional experimental measurements not discussed in the body of the report.

Appendix B – Simulation Methods

To predict the energy consumption of tankless water heaters for this study, an accurate thermodynamic model was needed. While a variety of models exist with different levels of complexity, e.g., [8], the Lumped Heat Capacity (LHC) model originally developed at NREL [7] offered the right mix of complexity and simplicity. The advantage of this model is that it can be used to accurately predict the energy consumption of the water heater when subjected to realistic draw patterns and mains temperatures, which would otherwise be very time consuming to do in the lab [1] [9]. At the same time, this model can be readily implemented with tools such as EnergyPlus and to predict annual gas consumption in different climates and use cases.

The LHC model (1) is typically characterized by just three parameters.

$$C * \frac{dT_{\mathrm{TWH}}}{dt} = \eta \dot{Q}_{\mathrm{gas}} - \dot{m} c_p (T_{\mathrm{TWH}} - T_{in}) - UA * (T_{\mathrm{TWH}} - T_{env}) \quad (1)$$

- C – thermal capacitance of the heat exchanger
- η – steady state combustion efficiency
- UA – standby loss coefficient of the heat exchanger relative to ambient

The other terms in equation (1) are T_{TWH} tankless outlet temperature, $\dot{Q}_{\mathrm{gas}}$ is the firing rate, $\dot{m}$ is the mass flow rate of water, c_p is the specific heat of water, T_{in} is the inlet water temperature, and T_{env} is the temperature of the ambient environment. The model was integrated using the forward Euler method with 5-second draw data from the expeirments and 1-minute DHW demand data from EnergyPlus.

Special tests were conducted as part of task one to infer these parameters, illustrated in Figure 11. Two larger draws and two small draws with 2-hour standby periods in between were used as a training data set to provide an initial estimate of the LHC model parameters. It was found that a fourth parameter, $Qoverfire$, was needed to accurately predict heat delivered as well. This parameter accounts for slightly increased firing rate at the beginning of a draw.

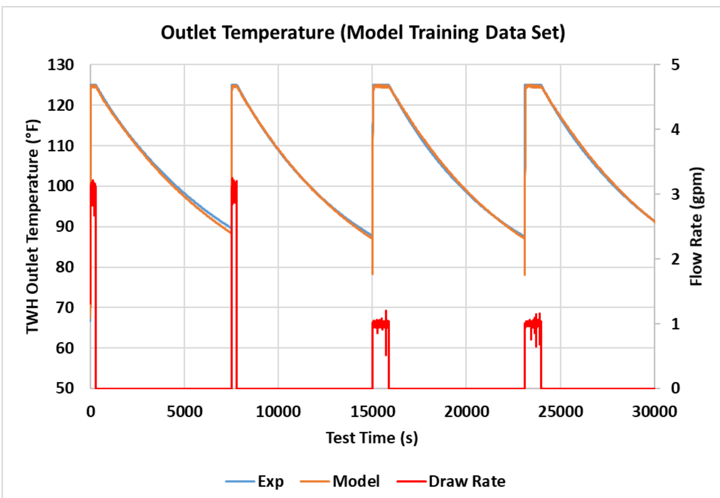

Figure 11 Model predictions compared to the training data set

The LHC model for each water heater was then optimized against the 24-hour UEF tests, using the training data set results as the initial guess. The optimization was performed using the nonlinear, generalized reduced gradient algorithm. Final model fits, while not perfect, could predict gas consumption and heat delivered to within 3% or less. Figure 12 and Figure 13 illustrate the quality of the fit and the predictive capability of the LHC model for the Model D water heater.

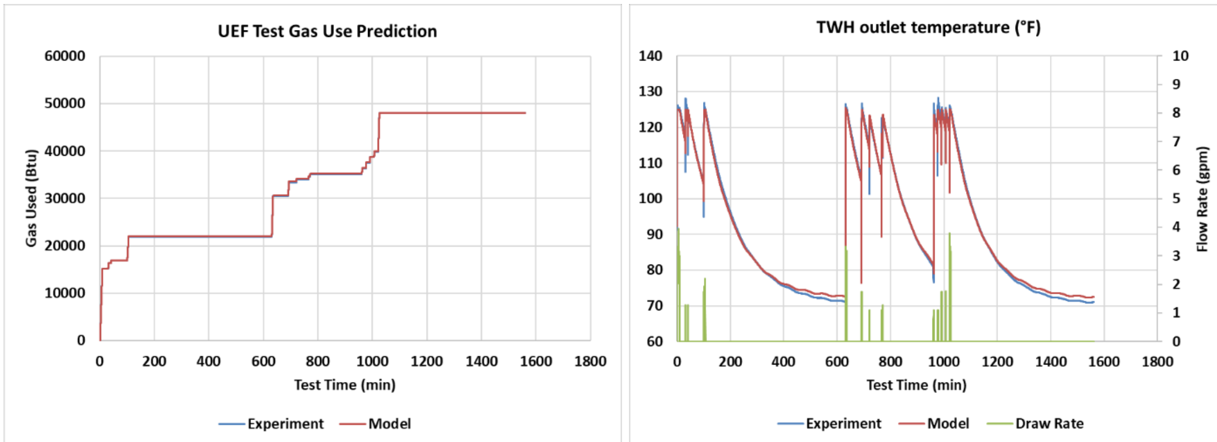

Figure 12. Predicted and experimental gas use (Left) and overall tankless temperature (Right) during the 24-hour UEF test

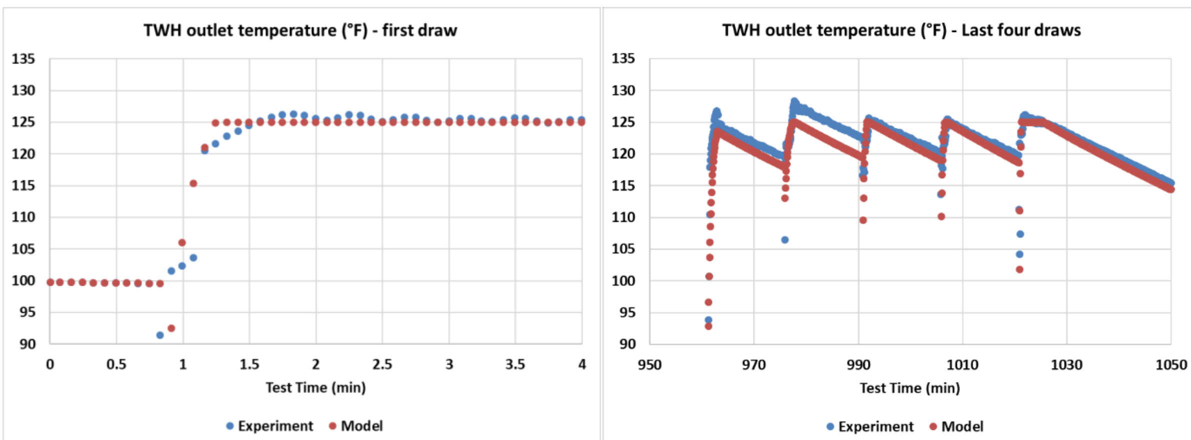

Figure 13. Predicted tankless outlet temperature compared to experimental measurements

Table 8 summarizes the inferred LHC model parameters for each tankless water heater tested. These parameters are similar in magnitude to prior studies [1] [7], however it is interesting to note that all of the parameters are similar in magnitude, despite differences in the actual water heater models. This is likely due to a statistical coupling between all four parameters in the optimization algorithm.

Table 8. LHC Model parameters for each water heater

Water heater	C [Btu/°F]	UA [Btu/hr-°F]	η_{ss}	Qoverfire [Btu/hr-gpm][2]
Model A	4.713	2.730	86.7	38534
Model B	4.559	2.375	97.3	35477
Model C	4.478	2.263	99.3	34251
Model D	5.675	3.029	98.2	36085
Model E	4.221	2.050	98.4	34102
Model F	4.522	2.270	98.5	36357
Model G	3.893	1.930	96.6	34878

[1]Used in energy savings and economic assessment
[2]Used only for estimate heat delivered

The model predictions of each water heater are compared in Figure 7. Despite the differences in rated UEF values, the performance characteristics of all the condensing tankless water heaters were similar. Model F water heater had performance characteristics that split the difference between the other models. For this reason, its LHC parameters were chosen for the energy savings analysis in this study.

NFPA 54 – National Fuel Gas Code

NFPA 54 requires that the gas piping is sized to allow all the appliances to simultaneously operate at their maximum capacity while supplied with at least the minimum gas pressure required by each device, but without exposing any of the devices to pressures higher than the maximum allowable pressure specified for the device by the manufacturer (5.4.1). Load diversity factors are permitted for multifamily dwellings (5.4.2.3). Pipe can be sized with equations and tables provided in NFPA 54, other methods which are allowed by the jurisdiction authority, or according to the equipment manufacturer's specifications (5.4.3). The three methods provided by NFPA 54 are: Longest Length Method, Branch Length Method, and Hybrid Pressure Method (5.4). The Hybrid Pressure Method is used for higher pressure systems with long lengths of pipe with regulators installed prior to the end use devices and is not applicable for typical residential installations.

The Longest Length Method is the simplest, and most commonly used method for sizing of piping (6.1.1). It requires only the distance from the point of delivery, the gas meter, to the most remote device or appliance in the system for all the pipe sizing in the system. This "longest length" distance, together with the actual maximum capacity required for each branch, is used to size the pipe for each branch in the system regardless of the actual length of each individual branch. This method is conservative and can result in oversized pipe being used for some of the branches. For the Branch Length Method, the sizing of the main trunk, the section from the meter to the first branch, is done in the same way as the "Longest Length Method" in that the distance from the meter to the most remote appliance, or device, together with the total capacity of the system is used to size the main trunk. All the remaining branches are sized using the respective branch's total distance to the supply point (length of branch plus the main trunk length).

The relevant portions of pipe sizing charts for pressure drops of 0.3, 0.5, 3.0 (requires at least 8.0 inWC supply pressure), and 6.0 inWC (requires at least 11.0 inWC supply pressure) for schedule 40 metallic pipe are shown in Table 9 and Table 10. Even using the conservative Longest Length Method, the latter two pressure drops would allow the largest residential tankless water heaters (199 MBH) to be installed in systems where the most remote device is 40 feet (3.0 inWC pressure drop) and 90 feet (6.0 inWC pressure drop) away from the gas meter; however, those pressure drops require supply pressures higher than commonly seen residentially. The 0.3 and 0.5 inWC pressure drop charts are more commonly used for sizing residential systems.

Table 9. Excerpt from NFPA 54 for sizing 0.5 inWC ΔP gas lines

TABLE 6.2(b) *Schedule 40 Metallic Pipe*

												Gas:	*Natural*	
												Inlet Pressure:	*Less than 2 psi*	
												Pressure Drop:	*0.5 in. w.c.*	
												Specific Gravity:	*0.60*	
	Pipe Size (in.)													
Nominal:	½	¾	1	1¼	1½	2	2½	3	4	5	6	8	10	12
Actual ID:	0.622	0.824	1.049	1.380	1.610	2.067	2.469	3.068	4.026	5.047	6.065	7.981	10.020	11.938
Length (ft)	*Capacity in Cubic Feet of Gas per Hour*													
10	172	360	678	1,390	2,090	4,020	6,400	11,300	23,100	41,800	67,600	139,000	252,000	399,000
20	118	247	466	957	1,430	2,760	4,400	7,780	15,900	28,700	46,500	95,500	173,000	275,000
30	95	199	374	768	1,150	2,220	3,530	6,250	12,700	23,000	37,300	76,700	139,000	220,000
40	81	170	320	657	985	1,900	3,020	5,350	10,900	19,700	31,900	65,600	119,000	189,000
50	72	151	284	583	873	1,680	2,680	4,740	9,660	17,500	28,300	58,200	106,000	167,000
60	65	137	257	528	791	1,520	2,430	4,290	8,760	15,800	25,600	52,700	95,700	152,000
70	60	126	237	486	728	1,400	2,230	3,950	8,050	14,600	23,600	48,500	88,100	139,000

Table 10. Excerpt from NFPA 54 for sizing 3 inWC ΔP gas lines

TABLE 6.2(c) *Schedule 40 Metallic Pipe*

						Gas:	*Natural*		
						Inlet Pressure:	*Less than 2 psi*		
						Pressure Drop:	*3.0 in. w.c.*		
						Specific Gravity:	*0.60*		
INTENDED USE: Initial Supply Pressure of 8.0 in. w.c. or Greater.									
	Pipe Size (in.)								
Nominal:	½	¾	1	1¼	1½	2	2½	3	4
Actual ID:	0.622	0.824	1.049	1.380	1.610	2.067	2.469	3.068	4.026
Length (ft)	*Capacity in Cubic Feet of Gas per Hour*								
10	454	949	1,790	3,670	5,500	10,600	16,900	29,800	60,800
20	312	652	1,230	2,520	3,780	7,280	11,600	20,500	41,800
30	250	524	986	2,030	3,030	5,840	9,310	16,500	33,600
40	214	448	844	1,730	2,600	5,000	7,970	14,100	28,700
50	190	397	748	1,540	2,300	4,430	7,060	12,500	25,500
60	172	360	678	1,390	2,090	4,020	6,400	11,300	23,100
70	158	331	624	1,280	1,920	3,690	5,890	10,400	21,200

The "longest length" method would be overly restrictive to use at the lower pressure drops. For example, when sizing for a pressure drop of 0.3 inWC, the most remote device would need to be within 10 feet of the gas meter to allow for the installation of most tankless heaters which are typically rated in excess of 100 MBH. Regardless of the sizing method used, the largest capacity residential tankless water heaters (199 MBH) cannot be installed when sizing with either the 0.3 or 0.5 inWC pressure drop charts due to a maximum allowable capacity at 10 feet (shortest distance listed) being 131 for the former and 172 MBH for the latter pressure drop. The "branch length" method would allow for the installation of tankless water heaters rated at or below 131 MBH on a half-inch gas line if the total branch length (main trunk length plus branch length) suppling the water heater is 10 feet long or less. If the piping is sized for a 0.5 inWC pressure drop then tankless water heaters up to 172 MBH could be installed with a total branch length not exceeding 10 feet.

ANSI Z21.10.3 - CSA 4.3 - Gas-fired water heaters, volume III, storage water heaters with input ratings above 75,000 Btu per hour, circulating and instantaneous

ANSI requires water heaters to be tested at three different gas supply pressures: reduced (3.5 inWC), normal (7.0 inWC), and increased (10.5 inWC) (5.3.1). The increased test pressure may be higher than the specified ANSI pressure as long as the pressure does not exceed the maximum rated pressure of any of the control components (4.3.1.3j/5.3.1). Prior to the testing, the burners need to be adjusted to within two percent of the rated output at a normal gas supply pressure (7.0 inWC) while maintaining a manifold pressure of within 10 percent of the specified value by the manufacturer. Proper operation of the water heater is determined by withdrawing and analyzing gas emission samples (5.4.1). One sample is obtained after 15 minutes of operation at a normal (7.0 inWC) gas supply pressure, and another is obtained immediately afterwards after the water heater input rate has been increased to 106.25% of the input rate specified by the manufacturer. This is achieved by adjusting the regulator inside the water heater. Neither sample may exceed 400 ppm carbon monoxide on air-free basis. A third sample is extracted after the regulator has been set to the original input rate, the gas supply pressure was changed to the reduced pressure (3.5 inWC), and the device was allowed to operate for 5 minutes. The air-free carbon monoxide concentration may not exceed 200 ppm. An air free carbon monoxide concentration not in excess of 400 ppm must also be achievable for water heaters using natural gas as fuel when operating at normal input rate and 4.0 inWC supply pressure (5.4.3).

Water heaters are also tested for burner flashback at normal and reduced gas supply pressure by turning the burner off and back on after 15 minutes of normal operation. For water heaters with power burners (e.g. premix burners) the water heater must also ignite without delay at reduced and normal pressures when the supplied voltage is 85 and 110 percent of the voltage specified by the manufacturer (5.6.7). Water heaters where the input rate is controlled through the water flow are operated at normal gas supply pressure and the water flow rate is reduced until it just barely exceeds the point at which the device would shut off. The device is then inspected for carbon deposits, explosive gas mixtures, and safe operation (5.6.9). The time for gas supply shut off to occur in the event of flame loss may not exceed 90 seconds, and if flame re-ignition system exist then the reignition must occur within 0.8 seconds of flame loss (5.9.6). No requirements for gas shut off systems or safety features are specified in the case of insufficient or excessive gas pressures. Only a high water temperature automatic gas shut off system is required for water heaters (4.20.1).

Appendix D – Additional Experimental Results

Table 11. Supplemental parameters measured as part of the 24-hour UEF test

Model	Recovery Efficiency Measured[1,2]	Recovery Efficiency Reported[1,2,3]	Max GPM Measured	Max GPM Rated[3]
Model A	0.89	0.85	4.5	4.5
Model B	0.98	0.99	5.8	5.7
Model C	1.0	0.99	3.2	3.2
Model D	0.98	0.97	5.5	5.7
Model E	1.0	0.96	3.3	3.7
Model F	1.0	100	5.4	5.4
Model G	0.96	0.97	5.1	5.4

[1]Recovery efficiency of 100% is possible due to residual heat stored in the water heater from the max GPM test
[2]Recovery efficiency reported by OEM is not verified by AHRI
[3]According to AHRI Directory of Certified Product Performance

Table 12. Range of CO and NOx emissions recorded during the first two draws of the UEF test

	CO Emissions (ppm) Corrected to 3% O_2		NOx Emissions (ppm) Corrected to 3% O_2	
Model	Minimum	Maximum	Minimum	Maximum
Model A	91.6	93.3	8.3	9.2
Model B	34.6	49.8	14.4	15.2
Model C	41.8	81.2	23.5	25.4
Model D	8.6	30.9	10.4	13
Model E	11.4	18.9	11.8	14.4
Model F	70.5	91.1	15.2	22.4
Model G	71.1	160.0	13.3	14.3

Table 13. Peak CO and NOx emissions at maximum firing rate

Model	CO Emissions (ppm) Corrected to 3% O_2	NOx Emissions (ppm) Corrected to 3% O_2
Model A	132.4	17.2
Model B	108.2	17.0
Model C	134.3	17.0
Model D	91.0	20.1
Model E	54.2	13.9
Model F	99.6	16.8
Model G	184.2	22.9

Appendix E – Additional Simulation Results

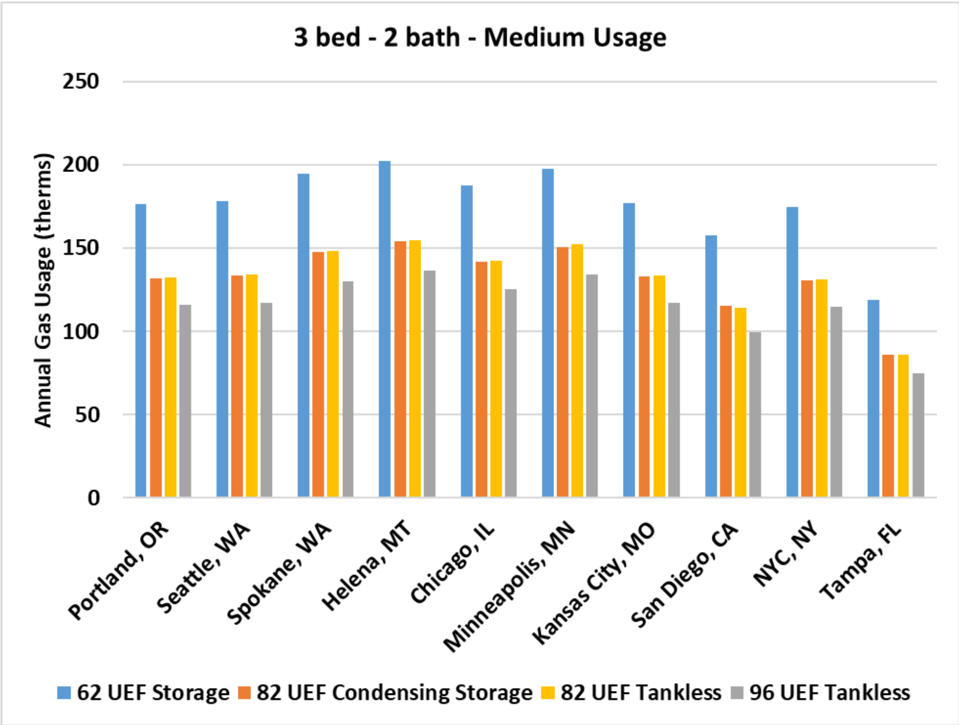

Figure 14. Annual gas consumption for all water heater options considered.

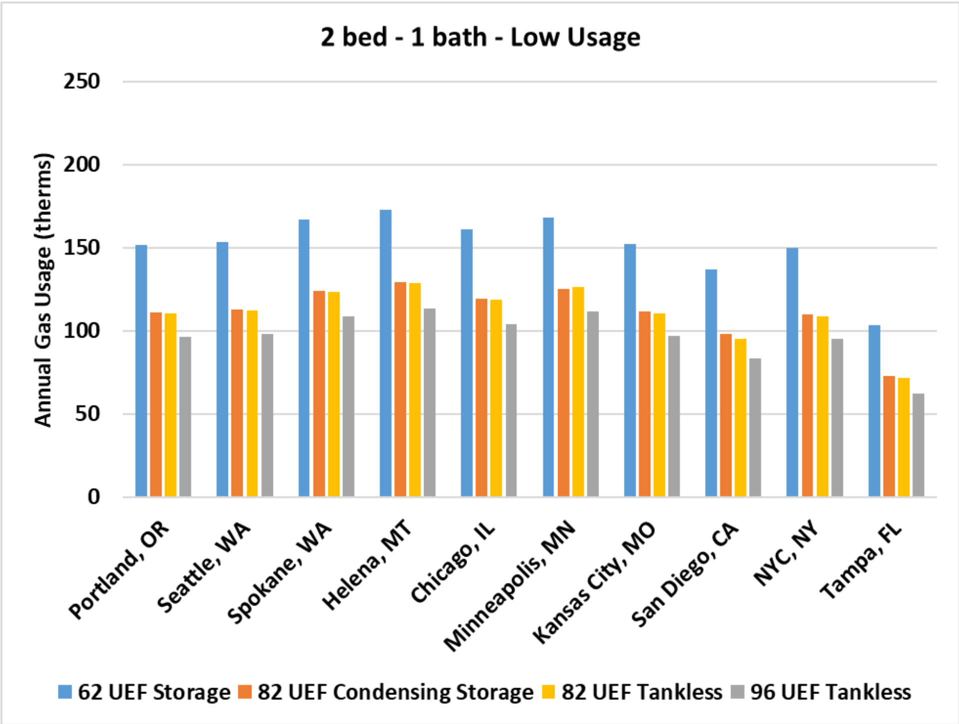

Figure 15. Annual gas consumption for all water heater options considered.

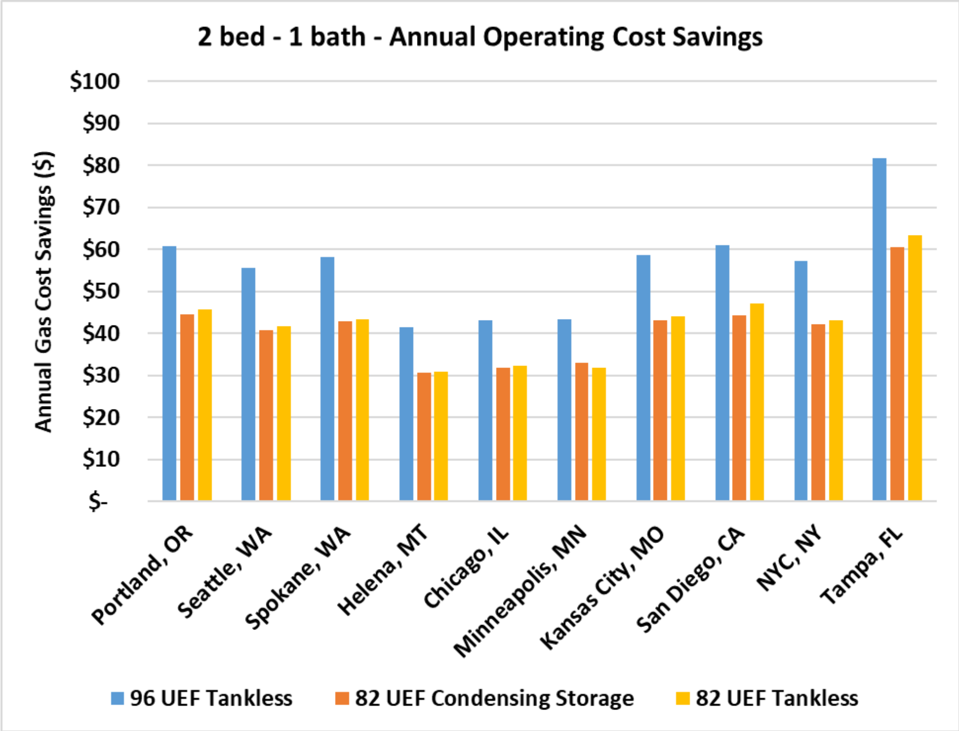

Figure 16. Annual operating cost savings

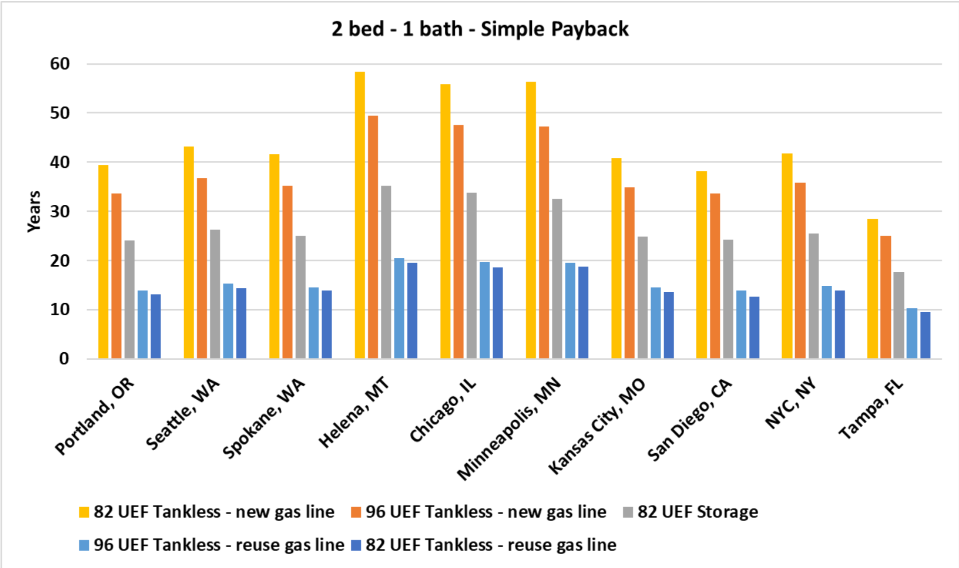

Figure 17. Estimated simple payback for tankless and condensing storage retrofit scenarios