ENERGY CENTER
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Energy Use by Residential Gas Water Heaters

A technical field study in 10 Wisconsin homes

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PROJECT SUMMARY

As part of a larger national project investigating the performance of residential gas-fired water heaters, the Energy Center of Wisconsin has monitored and evaluated performance of several types of water heaters in 10 southern Wisconsin homes.

The project included 10 existing natural draft water heaters (ranging from 5 to 31 years old), 10 replacement water heaters (power vent and tankless) as well as one short term replacement natural-draft water heater.

EFFICIENCY

Hot water usage among the households ranged from 27 to 135 gallons per day. Overall water heater input-output efficiency (defined as hot water energy out divided by gas energy in), averaged over the monitoring period for each system, ranged from 37 to 67 percent for natural-draft water heaters. Surprisingly, using instantaneous combustion efficiency as a metric, heavy mineral accumulation found in two of the natural-draft water heaters did not appear to reduce efficiency by a significant amount. For non-condensing power-vent water heaters, average input-output efficiency ranged from 56 to 71 percent, while for a single condensing-type power vent unit, efficiency was 83 percent. Non-condensing tankless units had average efficiencies from 75 to 80 percent, and a single condensing tankless model showed an average efficiency of 89 percent.

Operating Costs and Savings by Water Heater Type

Annual median estimated operating costs (normalized to a 60F temperature rise, and hot water usage of 75 gallons per day) for water heaters in each technology category are:

Natural-draft (n=11)	$237
Power-vent (n=4)	$214
Condensing power-vent (n=1)	$198
Tankless (n=4)	$181
Condensing tankless (n=1)	$159

These values are based on natural gas at $1.00 per therm, and electricity at $0.12 per KWH.

The added electric energy use in power-vent and tankless water heaters increase operating costs by a modest amount: generally less than $15 per year, depending on how much hot water is used and the type of water heater.

Energy savings for power-vent and non-condensing tankless models (compared to conventional natural-draft water heaters) derive primarily from reduced standby losses, and these savings are relatively insensitive to hot-water usage. Our analysis suggests annual savings of about $20 to $25 for a power-vent water heater, and $50 to $60 for a tankless unit.

Condensing water heaters, on the other hand, are inherently more efficient at producing hot water: with these systems, the savings increase with increasing hot-water usage. For typical hot-water usage in the range of 50 to 75 gallons per day, our data suggest \$30-40 per year savings for a condensing power-vent water heater and \$70-80 for a condensing tankless water heater—though these figures are based on monitoring a single unit of each type.

Induced Infiltration Load

The average total volume of room air exhausted through the venting system of natural-draft water heaters varies from home to home, ranging from about 7 to 23 cfm during main burner operation. During operation of the pilot light only, average vent flow ranged from 4 to 10 cfm, about half that of main burner operation, although the gas input of the pilot lights is typically less than 2 percent that of the main burner.

A portion of this flow of house air out through the venting system represents a marginal increase in total home air leakage, which in turn increases heating loads. We estimate the heating energy impact of the marginal infiltration associated with natural-draft water heaters in a southern Wisconsin climate at about 5 to 15 therms annually.

SPILLAGE AND BACKDRAFTING

Combustion products spillage during the first minute or two of main burner ignition was a common occurrence among the natural-draft systems studied, with normal vent flow being established within two minutes in most cases. There were infrequent cases of brief intermittent spillage later in the firing cycle, likely due to wind gusts. We did identify six cases of significant spillage after the first two minutes of main burner operation that lasted at least one minute. Several of these cases were associated with flow reversal in the vent system that started during pilot-only operation and continued through a substantial period (up to at least 15 minutes) of main burner firing.

HOT-WATER USAGE PATTERNS

When a hot water event is defined as consecutive five-second periods with some measurable water draw in each, a large fraction of events and total hot water volume occurs in events of under about 2 gallons. Many households show a spike in event volume at around 10 gallons, which is likely a signature of showering. Hot water delivery temperature tends to drop off more suddenly in water heaters in which the dip tube has disintegrated, which allows mixing of cold with hot water near the top of the tank.

SATISFACTION

Based on an informal telephone survey, homeowners involved in the project were uniformly satisfied with new power-vent and tankless water heaters. Some participants noted that it took a brief period to become accustomed to a time lag in the delivery of hot water from a tankless water heater, and the owners of the condensing tankless model commented on irregular temperature control that required careful adjustment of shower water temperature. And in one case, the dishwasher in a home supplied with a tankless water heater did not draw water at a sufficient rate to trigger water heater operation.

INTRODUCTION

Water heating represents about 20 percent of total residential end use energy consumption in the U.S., at about 19.2 million Btu in end use energy per household annually, or 2.1 quadrillion Btu in end use energy nationally. Of this, about 1.56 quadrillion Btu, or 74 percent, is supplied by natural gas or LP gas.[1]

While water heater performance has improved over time, many aspects of water heater and system performance are still not well understood. Under the umbrella of a U.S. Department of Energy State Technologies Advancement Collaborative (STAC) project, the Energy Center of Wisconsin and several other organizations[2] have investigated the performance of, and possible efficiency improvements to, residential gas-fired water heaters.

The majority of funding for Energy Center work under the project was provided through a grant from the Wisconsin Department of Administration, Division of Energy Services. The AO Smith Corporation provided replacement water heaters for the project.

The Energy Center's role in the project was to perform field monitoring of installed gas water heaters, including existing natural-draft storage water heaters, and replacement power-vent and tankless units. The objectives of the Energy Center's work include:

- Determination of the infiltration implications of natural-draft and power-vent water heaters on residences in a northern climate.
- Characterization of the overall operating efficiency of natural-draft, power-vent, and tankless water heater as installed in residences.
- Characterization of combustion products spillage in natural-draft water heaters in a northern climate.

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[1] U.S. Dept of Energy, Energy Information Administration, 2005 Residential Energy Consumption Survey 2http://www.eia.doe.gov/emeu/recs/recs2005/c&e/summary/pdf/tableus14.pdf and http://www.eia.doe.gov/emeu/recs/recs2005/c&e/summary/pdf/tableus12.pdf

[2] Brookhaven National Lab, Lawrence Berkeley National Lab, and American Council for an Energy Efficiency Economy

APPROACH

Our approach to this project was based on monitoring the performance of water heaters as installed in 10 homes, including natural-draft water heaters as found in each home, and replacement units of several types installed during the course of the project.

Participating households were selected from a group of volunteer households. We intentionally included homes with several water heater venting configurations in the study. As such, the sample is not random, and should be viewed as characterizing a range of performance and not necessarily representative of average water heater performance in Wisconsin homes.

The study homes are all wood-frame construction with full basements, and all the water heaters (existing and replacement) were installed in basements. The homes are in the southern Wisconsin counties of Dane, Sauk, and Juneau, within 60 miles of Madison.

Nine of the original water heaters (i.e. the water heaters installed in the test homes when the project started) were conventional, non-FVIR storage tank units, while one was an FVIR model.[3] The tank capacity of each was 40 or 50 gallons, and the date of manufacture ranged from 1977 to 2003 (see Table 1). All were vented via vertical, natural-draft chimneys. Three of the 10 original water heaters shared a chimney with a furnace or boiler. More information on the homes and water heaters can be found in Appendix A.

TABLE 1. WATER HEATER TYPES STUDIED

Site	Existing or replacement	Type
A	Existing	Natural-draft storage tank
B	Existing	Natural-draft storage tank
C	Existing	Natural-draft storage tank
D	Existing	Natural-draft storage tank
E	Existing	Natural-draft storage tank, FVIR design
F	Existing	Natural-draft storage tank
G	Existing	Natural-draft storage tank
H	Existing	Natural-draft storage tank
I	Existing	Natural-draft storage tank
J	Existing	Natural-draft storage tank
A	Replacement	Tankless
B	Replacement	Condensing tankless
C	Replacement	Power-vent storage tank
D	Replacement	Power-vent storage tank
E	Replacement (short term only)	Natural-draft storage tank, FVIR design
E	Replacement	Tankless
F	Replacement	Condensing power-vent storage tank

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[3] FVIR, or flammable vapor ignition resistant design, intended to prevent the ignition of vapors such as gasoline that accumulate near a water heater, has been required in new water heaters in the U.S. since 2003.

Site	Existing or replacement	Type
G	Replacement	Power-vent storage tank
H	Replacement	Tankless
I	Replacement	Tankless
J	Replacement	Power-vent storage tank

After monitoring the performance of the original natural-draft water heaters for a period of about 9 to 12 months, we replaced each water heater and continued monitoring. The replacement water heaters were of several types. Four were power-vent storage tank units that use a blower to exhaust combustion products horizontally (or vertically) through PVC pipe. One was a condensing-efficiency power-vent unit, which is designed for higher thermal efficiency. Four replacements were tankless water heaters of non-condensing design. Tankless (or instantaneous) water heaters do not store a significant volume of hot water, but heat the water as it flows through to the end use. The model we installed uses a concentric PVC and aluminum system for fan-assisted horizontal or vertical venting. One replacement was a condensing-efficiency tankless model, again designed for higher thermal efficiency than the non-condensing tankless models, with fan-assisted intake and exhaust venting via PVC pipe. We monitored these replacement water heaters for about 6 to 9 months.

We also installed one new natural-draft water heater for a shorter test period. Only one of the existing natural-draft water heaters we found in the study homes was an FVIR model. With the intent of investigating any systematic differences between FVIR and conventional natural-draft units, we replaced the original water heater in one home with a new natural-draft FVIR water heater and monitored it for 82 days before installing the final replacement unit.

We made an effort to avoid disrupting the normal hot water usage patterns of participants, and did not request or make any changes in hot water temperature setpoint.

MEASUREMENT

To meet the objectives of the project, we designed a monitoring system to provide data on hot water usage and temperatures, energy inputs (gas and electric), venting system and zone pressures, combustion products gas concentrations and temperature measurements for calculation of vent system flows and identification of spillage events, and related environmental factors including several temperature measurements. See Table 2 for a summary of measurement parameters.

TABLE 2. SUMMARY OF MEASUREMENT PARAMETERS

Measured parameter	**Use of this parameter**	**Used primarily for this system type**
Water flow to water heater	Hot water loads	All
Hot and cold water temperatures	Hot water loads	All
Room temperature (near floor, and near draft hood)	1) Energy balance of air, fuel, and combustion products, 2) As an indicator of vent spillage	All
Outdoor temperature	Explanatory factor in vent flow variation	Natural-draft
CO_2 and CO in room air and combustion products (measured in room air during pilot light and main burner operation, measured in vent system only during pilot light operation only)	1) Stoichiometric calculation of total vent flows during pilot light operation, 2) Identification of combustion products spillage, 3) Detection of significant CO production	Natural-draft
Oxygen in venting system (monitored occasionally using 2 sensors rotated among sites, measured in vent only)	Stoichiometric calculation of total vent flows during main burner operation.	All
Vent-Basement differential pressure	For correlation to stoichiometric flow values, used to extrapolate to flows when gasses not sampled.	Natural-draft
Differential pressure, Outdoor-Basement	1) For investigation of vent spillage conditions, 2) As an indicator of windy conditions that affects vent flows	All
Main burner operation (on-off status) via gas pressure switch	Burner on time. Gas flow measured using time lapse photos and/or pulsing meters.	Natural-draft and power-vent
Gas flow via pulse-output gas meter	Gas input	Tankless
Current draw	Proxy for power consumption, calibrated using short-term real power measurement	Power-vent and tankless

Measurement and analysis methods differed in some ways for each water heater type. Carbon dioxide measurements were used with natural-draft water heaters both for off cycle (pilot light only) vent flow measurement and to identify spillage, but were dropped for power-vent and tankless systems which have no pilot lights and are not susceptible to spillage. Electric power measurement was added for power-vent and tankless systems. While a constant main burner gas flow was assumed for the non-modulating systems (natural- draft and power-vent), pulse-output gas meters were added to measure modulating gas input for tankless systems.

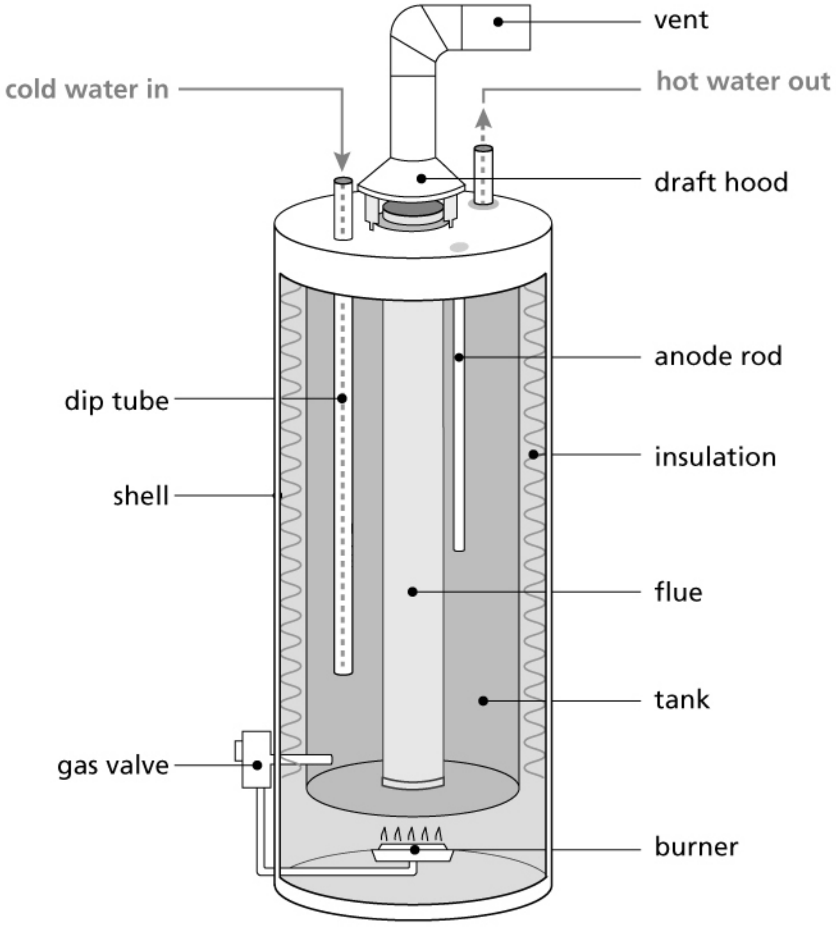
The system recorded data at five-minute intervals during off-cycle operation, but switched to five-second recording whenever the water heater main burner operated (and for a 20-minute post-firing period). Hot-water usage was recorded at a five-second time interval throughout. We also make use of some very high time-resolution data (one-second) that we recorded for each site.

More detail on the monitoring system and analytic methods is included in Appendix B.

GAS WATER HEATER CONSTRUCTION

Figure 1 shows the typical components of a natural draft gas water heater in cross-section.

FIGURE 1. WATER HEATER CROSS-SECTIONS



The dip tube is intended to carry incoming cold water to the bottom part of the tank, thus maintaining stratification of temperatures from coldest near the bottom to hottest at the top. This in turn increases the amount of hot water that can be drawn from the system before delivery temperature drops off to unacceptable levels.

The anode rod is a metallic element designed to oxidize more readily than the steel tank wall. It protects the tank from oxidation, lengthening tank life.

Mineral buildup is common in water heaters, as increased temperatures drive calcium and magnesium carbonates out of solution. This buildup may be expected to reduce water heater efficiency (by reducing conduction from the burner through the bottom of the tank to the water), and to reduce the life of water heater tanks (by increasing corrosion rates).

INSPECTION OF WATER HEATERS REMOVED FROM SERVICE

After removal from service, we cut open the tanks of the 10 original water heaters for inspection. In each case, we noted the approximate volume of mineral buildup, the condition of the dip tube, and the condition of the anode rod (see Table 3). The implications of mineral accumulation and dip tube integrity are discussed in later sections of this report.

TABLE 3. CONDITION OF EXISTING WATER HEATERS AFTER REMOVAL FROM SERVICE

Site	Year of manufacture	Water softener in place?[4]	Volume of mineral accumulation (gallons)	Dip tube condition	Anode rod condition
A	1977	Yes	Less than 0.03	Disintegrated	Completely eroded
B	1998	Yes	Less than 0.03	Intact	Largely intact
C	2000	No	More than 2.0[5]	Intact	Largely intact
D	1993	Yes	None	Broken off[6]	Completely eroded
E	1991	Yes	Less than 0.03	Long crack[7]	Completely eroded
F	2003	No	More than 2.0	Intact	Completely eroded
G	1993	Yes	None	Intact	Completely eroded
H	1991	No	Approx 0.1	Intact	Completely eroded
I	1992	No	Approx 0.5	Long crack	Completely eroded
J	1986	No	Approx 0.2	Disintegrated	Completely eroded

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[4] We did not evaluate actual mineral conditions in the water

[5] In both cases of the heaviest buildup of mineral material, the material formed a solid cake in the bottom of the tank

[6] We suspect this dip tube, which was otherwise largely intact, broke off in transport after the water heater was removed from service

[7] "Long crack" refers to longitudinal cracking of the dip tube. In both cases where we observed this, the dip tubes had straight, parallel cracking along opposite sides nearly their entire length.

RESULTS

VENT FLOW

A primary objective of the study was to determine how much air goes up the venting system of a conventional natural-draft water heater, and how this affects home heating loads. We used gas input rates and measured concentrations of combustion products as a primary method for determining venting flows, and correlated flow with pressure drop at the draft hoods to allow extrapolation of flows across all conditions. (See Appendix C for more information.)

Observed Vent Flow in Natural-Draft Water Heaters

Figure 2 shows two-hour traces of calculated vent flow (above the draft hood) for three of the sites, based on vent-measured vent pressures. There is a readily apparent increase in vent flow during main burner operation. This difference is driven largely by higher vent temperatures during burner operation (on cycle).[8] Note that, while the main burner gas input is about 100 times the pilot light input in each of these systems [check values for systems selected], the vent flow under off cycle conditions is roughly half that during on cycle. This is typical of the systems investigated, and is due to the fact that, as in many fluid systems, frictional effects are a non-linear function of flow rate. The vent flow differences among systems show some correlation to chimney height, as expected.

The effect of wind on short-term variation in vent flow can also be seen in the top three traces in Figure 2. Winds (as measured at the Madison airport) were calm during the time recorded by the top trace, were moderate in the second trace, and were gusty in the third trace.

We also found that operation of the heating system can have a significant influence on water heater vent flow when the two share a venting system, as was the case at Sites D, F, and H—though the nature of the influence depends on site-specific factors. As Figure 2 shows, at Sites D and F, airflow through the water heater's portion of the vent system increased when the forced-air furnace fired. This is an expected consequence of increased temperature in the chimneys when the furnace fires.[9] At Site H, an electrically activated flue damper opens before the boiler main burner fires. The open damper represents a large source of additional airflow into the venting system, the effect of which is to increase pressure drop along the venting system and decrease flow through the water heater vent. When the boiler fires, vent temperatures and driving forces increase, and water heater vent flow recovers somewhat—though it is generally lower during boiler firing than with the boiler off.

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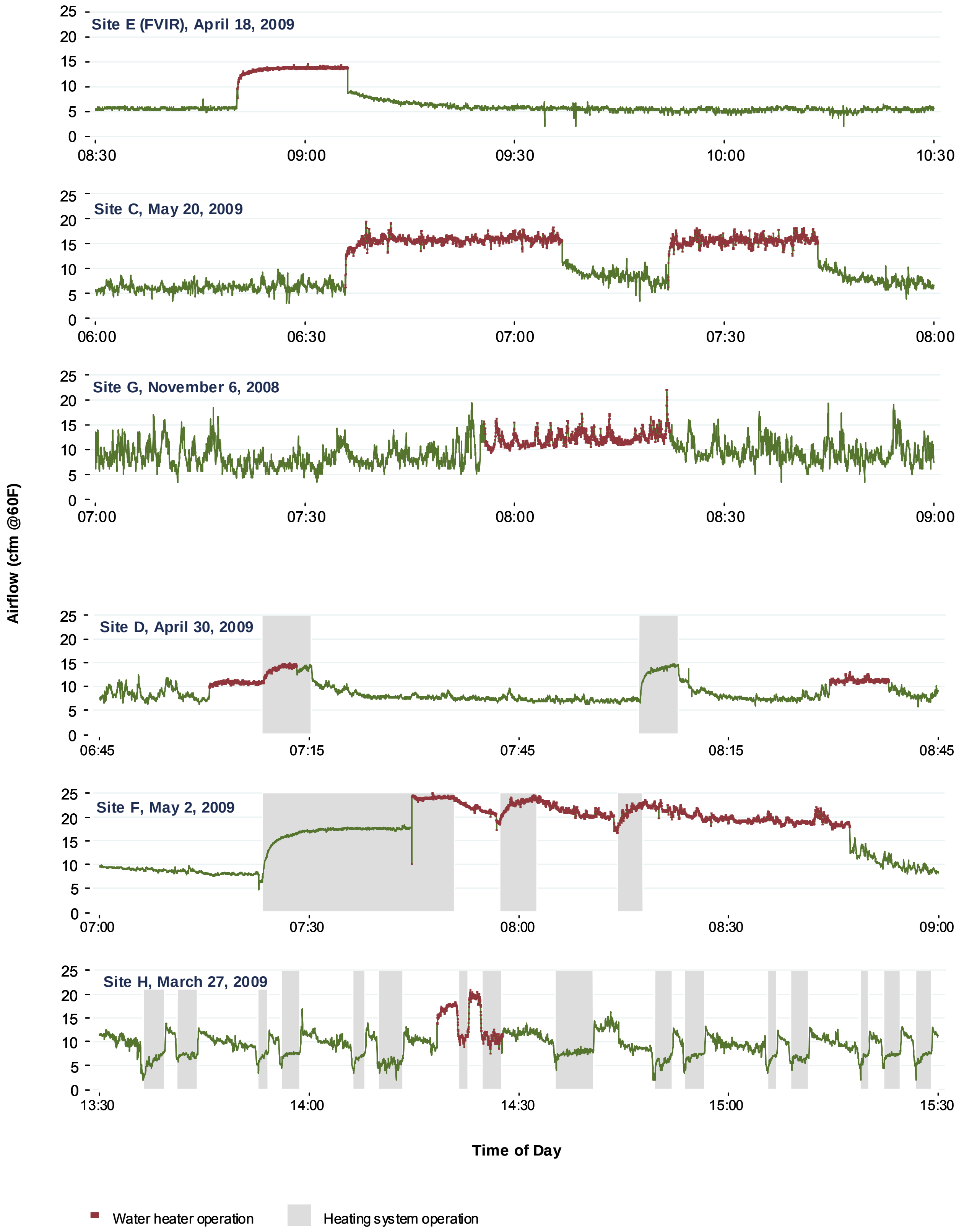
[8] Discussion of vent flow driving forces is included in Appendix B.

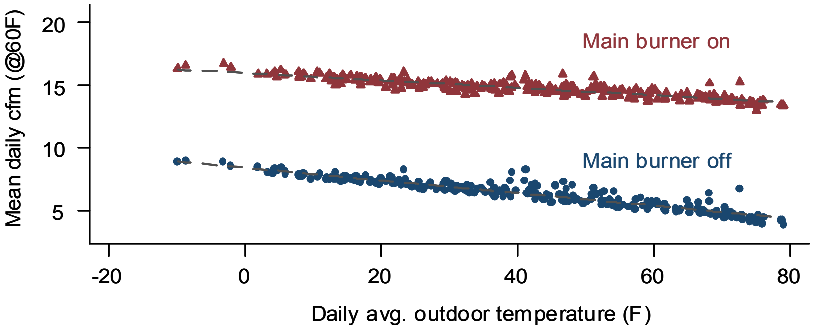
[9] Increased vent flow during heating plant operation also provides indirect evidence that the vent systems are adequately sized, since undersizing would increase pressure drop and could in some cases yield reduced water heater vent flow during furnace operation.

FIGURE 2. VENT FLOW EXAMPLES (TWO HOUR TRACES OF ONE SECOND DATA).



Although wind can add a significant amount of short-term variation to vent flow, we found that over the longer term, outdoor temperature is more important, due to its influence on stack effect. As Figure 3 shows, on a daily basis there is a clear (and strong) relationship between outdoor temperature and vent flow (similar graphs for all sites can be found in Appendix G). We used this relationship with long-term temperature data for Madison to model seasonal vent flow.

FIGURE 3. DAILY VENT FLOW VS. OUTDOOR TEMPERATURE, SITE C.



Average Seasonal Vent Flow

Using site-specific relationships between vent flow and outdoor temperature, and long-term average daily temperature data, we modeled seasonal and annual system vent flow for Madison, Wisconsin. The results suggest that off-cycle airflow through the venting system in most cases is between 10 and 20 cfm when the water heater is firing, and less than 10 cfm when the main burner is not firing (Figure 4). Because a water heater is typically firing less than 10 percent of the time, the overall average vent flow hews closely to the off-cycle flow levels.

FIGURE 4. ESTIMATED SEASONAL AVERAGE VENT FLOW FOR NATURAL-DRAFT WATER HEATERS, BY SITE AND WATER HEATER STATUS.

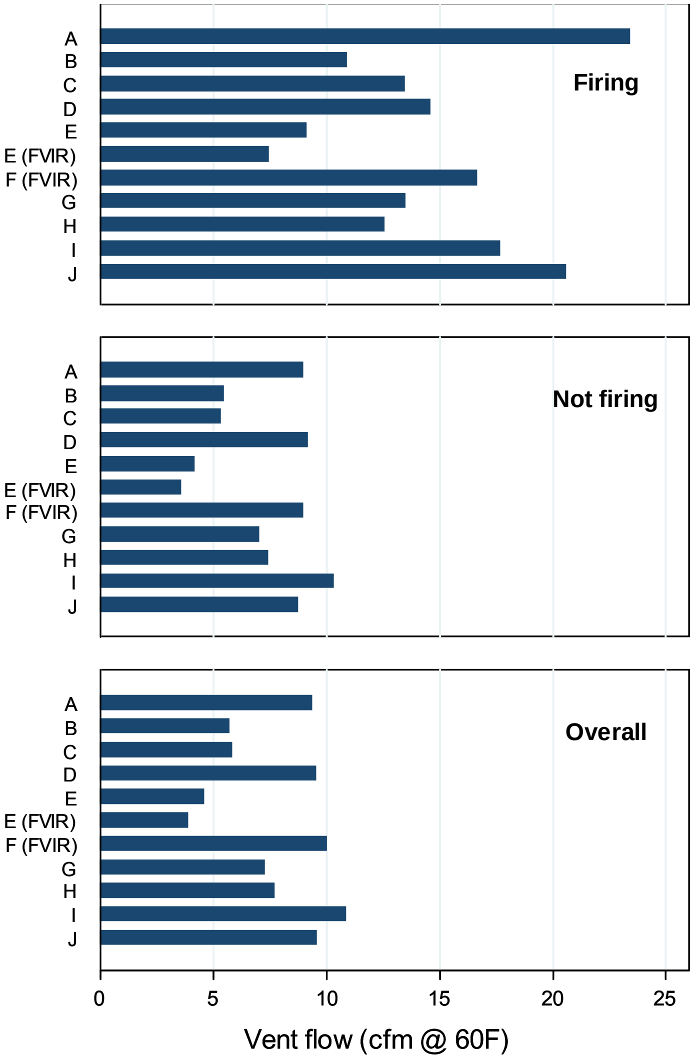
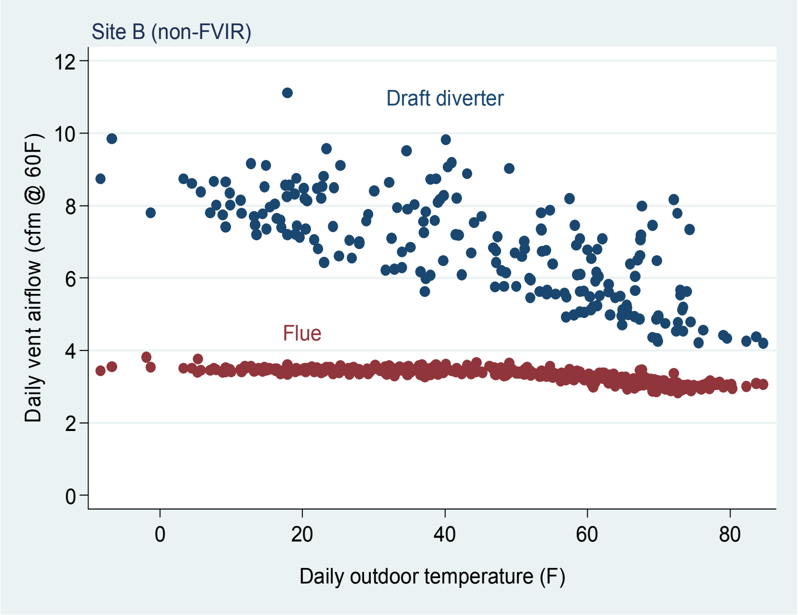


FIGURE 5. DAILY AVERAGE OFF CYCLE AIRFLOW THROUGH WATER HEATER FLUE AND DRAFT DIVERTER, VERSUS OUTDOOR TEMPERATURE (SITE B)



Also of some interest is the source of the air that flows through a natural-draft water heater's venting system. Air may enter the system either at floor level through the combustion chamber, or at the top of the water heater through the draft diverter. By comparing measured concentration of CO_2 outside the water heater, in the water heater flue and in the venting above the draft diverter, we could calculate the proportion of airflow from each location. (This applies to off-cycle conditions only, as we did not have equivalent gas measurements available during main burner operation.) We found that airflow through the water heater flue is fairly constant, with a slight coupling to total vent flow, while flow through the draft diverter is much more variable: the latter generally increases with increasing stack effect at colder outdoor temperatures, but also varies considerably depending on day-to-day variation in windiness (Figure 5). This evidence supports the idea that draft diverters are adequately performing their essential function of decoupling the water heater from the vagaries of wind and stack forces in the remainder of the vent system.

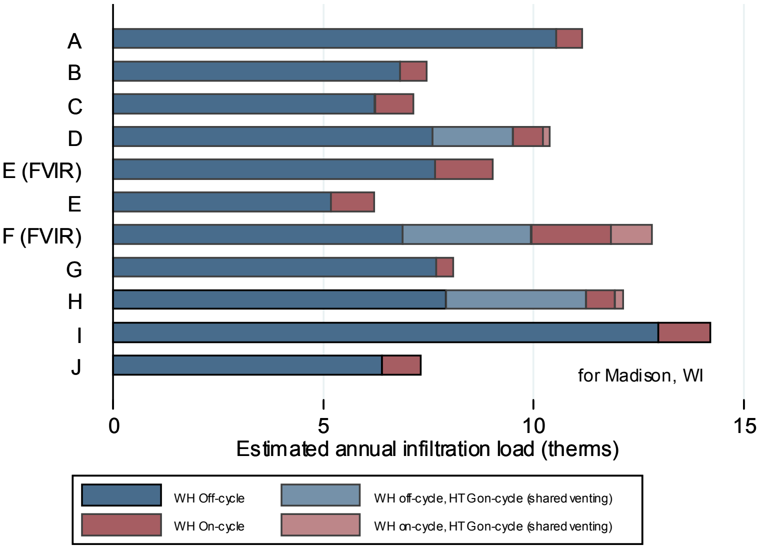
Power-Vented Water Heaters

We obtained (from measured O2 levels in the vent system and stoichiometry calculations) the on-cycle flow rates for four of the five power-vented replacements. The three non-condensing power-vented water heaters (at Sites D, G and J) showed airflow rates between about 55 and 70 cfm; the single condensing power-vented water heater in the study (Site F), had a much lower flow rate of 17 cfm.

INDUCED INFILTRATION LOAD

Airflow through a water heater's venting system adds to the space heating load of the home to the extent that it removes conditioned indoor air that is then replaced with unconditioned outdoor air. Under most conditions, when air is leaking in at some locations and out at other locations, a marginal increase in exhaust such as venting of the water heater yields an increase in total ventilation that is substantially smaller than the increase in exhaust flow. This is because part of the increased exhaust flow is typically offset by decreased exfiltration elsewhere. Based on methods described in Appendix C, we estimate that for the natural-draft water heaters in the study this heating load penalty is in the general range of 5 to 15 therms per year for Madison, Wisconsin (Figure 6). [10, 11]

FIGURE 6. ESTIMATED ANNUAL HEATING INFILTRATION LOAD PENALTY FROM NATURAL-DRAFT WATER HEATERS (FOR MADISON, WI), BY OPERATING MODE CONTRIBUTION



This analysis assumes that the home's heating system is needed to make up the entire temperature difference between the air entering the water heater and outdoor conditions. Because water heaters in northern climates are often located in semi-conditioned basements, this may not always be true, in which case the heating penalty would be less.

Conversely, a water heater may be located in a fully conditioned space, and thus create a greater infiltration penalty. However, our modeling suggests that even if all of the water heaters in the study were in conditioned spaces maintained at 68F throughout the heating season, the infiltration heating penalties would increase on average by only about 0.5 therms relative to the figure above.

The high airflow associated with the non-condensing power-vent water heaters amounts to a non-negligible fraction of our estimates for natural-draft water heaters: if a typical power-vent water heater fires about 5 percent of the time at about a 60 cfm vent system airflow, then the seasonal heating load penalty would be about 2.5 therms in Madison, WI. The heating load penalty of the condensing power-

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[10] Note that we report here the heating *load* penalty, without incorporating the efficiency of the heating system.

[11] We also estimated the infiltration penalty for other locations (Kansas City, Des Moines, Boston and Minneapolis), and found that the results scale linearly with heating degree days: e.g., Kansas City has about 40 percent fewer heating degree days than the 7,100 for our Madison weather data, and we estimated a corresponding 40 percent lower infiltration penalty using weather data for that location.

vent water heater, by contrast, would be only about 0.7 therms, owing to its much smaller vent flow rate. Tankless water heaters do not impose any infiltration heating burden because they have sealed combustion systems that do not interact with indoor air.

The heating energy penalty of vent airflow is just one aspect of whole-building performance in which water heaters interact with other systems. We have not attempted to quantify cooling load impacts of water heater venting. Other interactions between water heating systems and building conditioning not considered in this report include water heater jacket heat loss, heat loss in delivery of hot water, heat loss from hot water left in piping after a draw, and humidification effects of hot water usage. See Appendix E for further discussion.

WATER HEATER EFFICIENCY

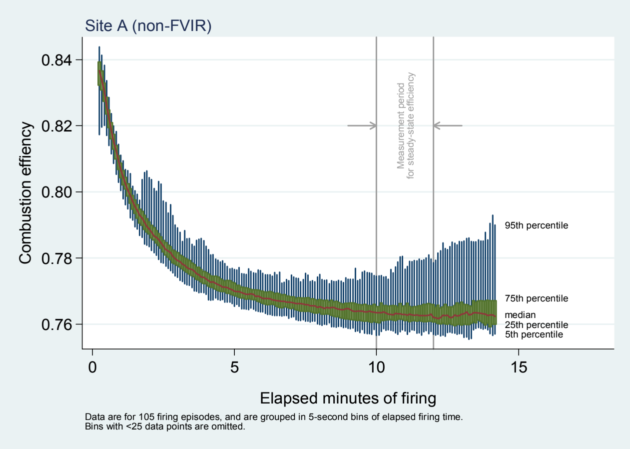
We considered water heater efficiency from two perspectives: (a) measured combustion efficiency based on the O_2 and CO_2 data that we collected; and (2) overall input/output efficiency based on comparing daily firing times (or measured gas input) to delivered hot water energy. We discuss each of these in turn.

Combustion Efficiency

Combustion efficiency is an instantaneous measure of the transfer of heat from combustion into water (see Appendix D for a more detailed discussion). The oxygen sensors that we rotated among the sites—along with measured vent and ambient temperatures—provided sufficient data for stoichiometric calculation of combustion efficiency during firing episodes. The CO_2 data also allowed us to calculate the combustion efficiency during off cycle (pilot only) operation of the natural-draft water heaters.

Calculated combustion efficiency is useful for setting an upper bound on overall water heater performance, as energy lost through the venting system is unrecoverable. And the effective combustion efficiency during off cycle operation of natural-draft units is one way of characterizing the excess losses associated with use and venting of a pilot light.

FIGURE 7. MAIN BURNER COMBUSTION EFFICIENCY AT SITE A.



Data are for 105 firing episodes, and are grouped in 5-second bins of elapsed firing time. Bins with <25 data points are omitted.

Figure 7 exemplifies what we observed among the natural-draft water heaters in the study during firing episodes: combustion efficiency is highest in the first few minutes of firing—as the hot flue gases encounter the coldest tank water temperatures, and on-cycle draft is not fully established—and then declines to a fairly stable value.

Taking the period between 10 and 12 minutes of firing as representative of steady-state conditions, the firing efficiencies for gas water heaters are generally in the range of 75 to 80 percent (Figure 7).

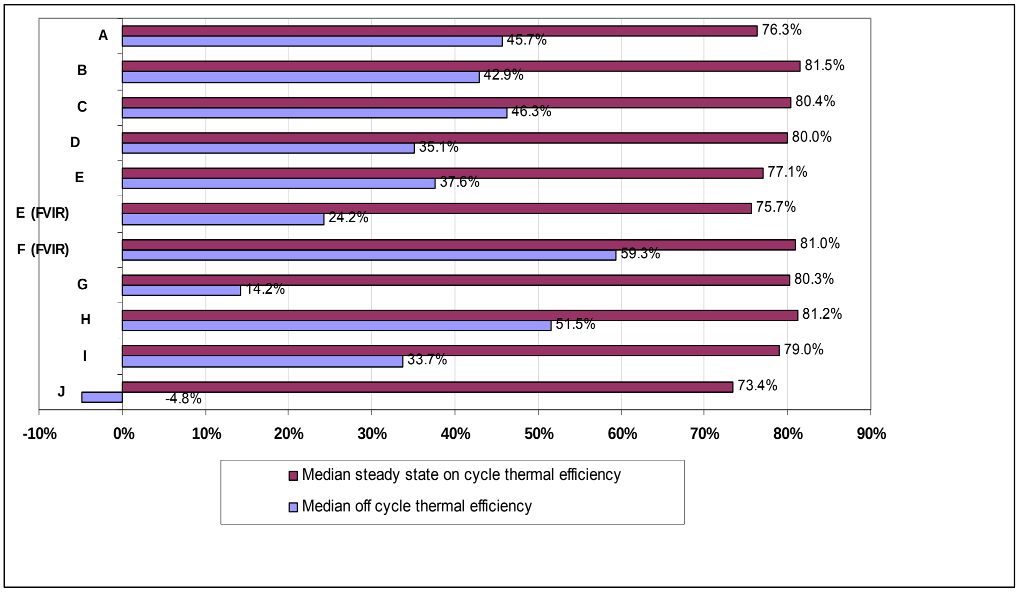
For all but one site, main burner operation accounts for 80 to 90 percent of the fuel consumption. The exception was Site A, where the pilot accounted for a remarkable 43 percent of gas use, owing to relatively high pilot gas input.

Note that the thermal efficiency of the original water heaters at sites D and F are among the highest here, in spite of the fact that they had by far the heaviest mineral buildup of the original water heaters. While the buildup of solid mineral material would seem likely to reduce heat transfer from the burner to the water in the tank, it's possible that the combination of direct thermal conduction from tank wall to the solid mineral mass, plus good conductivity and/or high thermal mass of the mineral block, means that heavy mineral buildup does not necessarily reduce performance significantly.

Thermal efficiency can be measured during pilot light operation exactly as during main burner operation, though the results tend to be skewed toward lower values. As noted earlier, the flue and vent flows during pilot-only operation typically include large fractions of excess air, thus reducing the temperature of combustion products and the amount of heat available to transfer to a sink of any given temperature. In addition, we found that the combustion products exiting water heater flues during pilot only operation tend to be near the set-point temperature, i.e. are in thermal equilibrium with the tank. Taken together, these factors mean off cycle thermal efficiencies can be expected to be uniformly lower than on cycle efficiencies.

The natural-draft water heaters in the study generally had off cycle combustion efficiencies that were in the range of 30 to 50 percent (Figure 8). Site J, however, had a negative pilot efficiency, indicating that the water heater was losing heat through the venting system at a rate that was greater than the heat provided by the pilot light. This site is notable in having a high vent flow rate, but more importantly for having a relatively high set-point (over 140F) that probably stemmed from the fact that (as we later discovered) the dip tube was broken off, thus decreasing the effective capacity of the tank (Figure 8). The combination of relatively high vent flow and high tank temperature combined to increase the off-cycle stack losses of the water heater.

FIGURE 8. COMPARATIVE ON AND OFF CYCLE COMBUSTION EFFICIENCIES FOR NATURAL-DRAFT WATER HEATERS



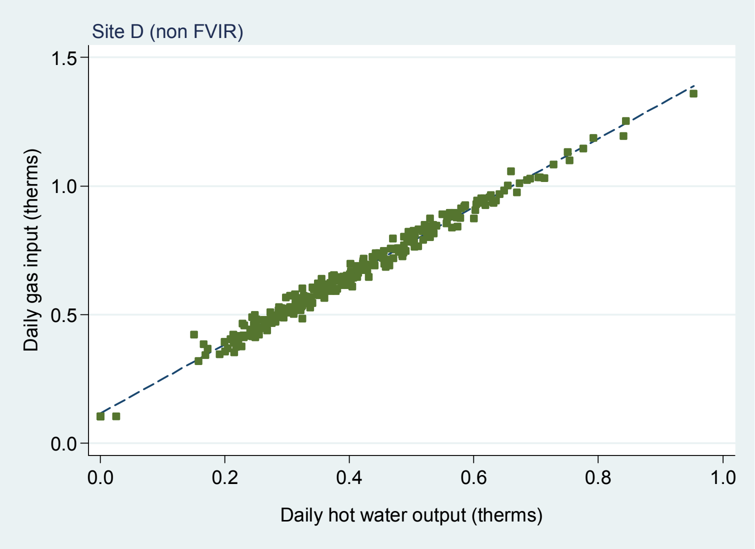
On-cycle combustion efficiencies for the four non-condensing units where we obtained this data (3 power-vents and one tankless) were in the range of 80 to 84 percent. The two condensing units (one power-vent and one tankless) had indicated combustion efficiencies of 88 to 90 percent, but these underestimate actual efficiency because they do not take into account condensation of water vapor in the flue gas, which we observed being produced by both water heaters.

Input/Output Efficiency

The ratio of useful hot water energy output to total gas energy input[12] offers a more robust measure of overall performance of a water heater than instantaneous thermal efficiency, for two major reasons. First, useful output is defined as hot water energy only, with all venting and tank shell losses combined, as is usually desired. Second, input/output efficiency is conveniently calculated on a daily or longer basis from hot water delivery and fuel input data, avoiding the need to integrate instantaneous thermal efficiencies over time.

We compared the daily BTU of natural gas burned by the water heater to the BTU of hot water delivered.[13, 14] Plots of the former versus the latter were highly linear for all of the water heaters in the study as exemplified in Figure 9 (see Appendix D for input/output plots for all sites). The slope of this relationship is related to the recovery efficiency of the water heater[15]: as expected, most were in the ballpark of the steady-state combustion efficiencies.[16]

FIGURE 9. DAILY INPUT/OUTPUT RELATIONSHIP FOR THE NATURAL-DRAFT WATER HEATER AT SITE D



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[12] We use the term "input/output efficiency" in this report.

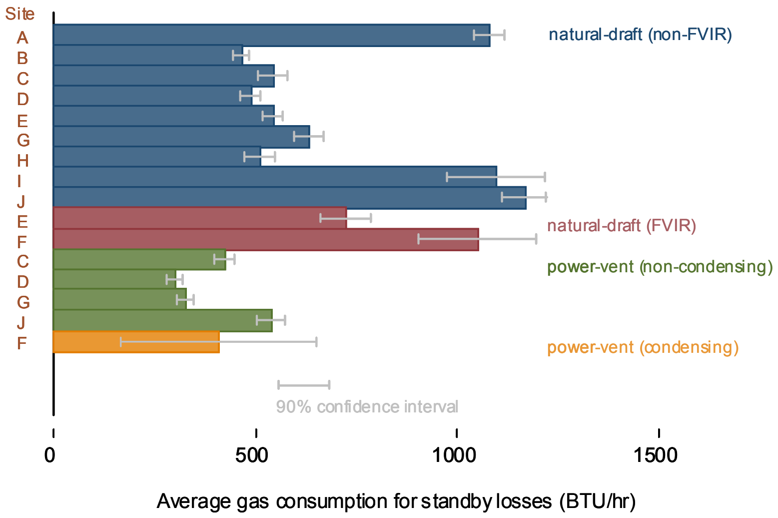
[13] Water heater output is the sum over time of the product, calculated every second, of flow, temperature difference, and specific heat.

[14] Note that this analysis does not consider distribution losses that may occur after water has left the water heater.

[15] The slope of the input/output relationship is not quite equivalent to instantaneous thermal efficiency, see Appendix D.

[16] An exception to this is Site I, which for reasons we were unable to determine, had a slope term that implied about 100 percent efficiency. Spurious water-meter pulses may be to blame here.

FIGURE 10. ESTIMATED GAS REQUIREMENT FOR STANDBY LOSSES, BY SITE AND WATER HEATER.



In the case of storage tank water heaters, the intercepts from these regressions approximates the input required to offset standby losses (including jacket and stack losses) at zero hot water load. As Figure 10 shows, these were highest for the natural-draft water heaters, which have significant off cycle stack losses. The overlapping range of values for FVIR and non-FVIR water heaters implies that there is no systematic difference in standby performance between these technologies. The lower intercepts for power-vent water heaters, on the other hand, is almost certainly due to the lower standby stack losses in these units, which do not have standing pilot lights.[17]

We also obtained small, but statistically significant intercept values for the tankless water heaters. While these intercepts have some relationship to losses from the thermal mass of the water heater after each draw, the value will vary with usage patterns (number of hot water draws, draw volumes, and time between draws), and should not be interpreted as having any physical meaning as these systems approach zero load, and as such are not shown.[18]

The fact that storage water heaters all have non-trivial standby losses means that water heater efficiency is a function of how much hot water is used. For households that use relatively little hot water, standby losses represent a relatively large proportion of the energy required by the water heater, and overall efficiency is low; as hot-water demand increases, the relatively fixed standby losses represent less and less of the total energy requirement, and the overall efficiency of the water heater begins to approach its combustion efficiency.

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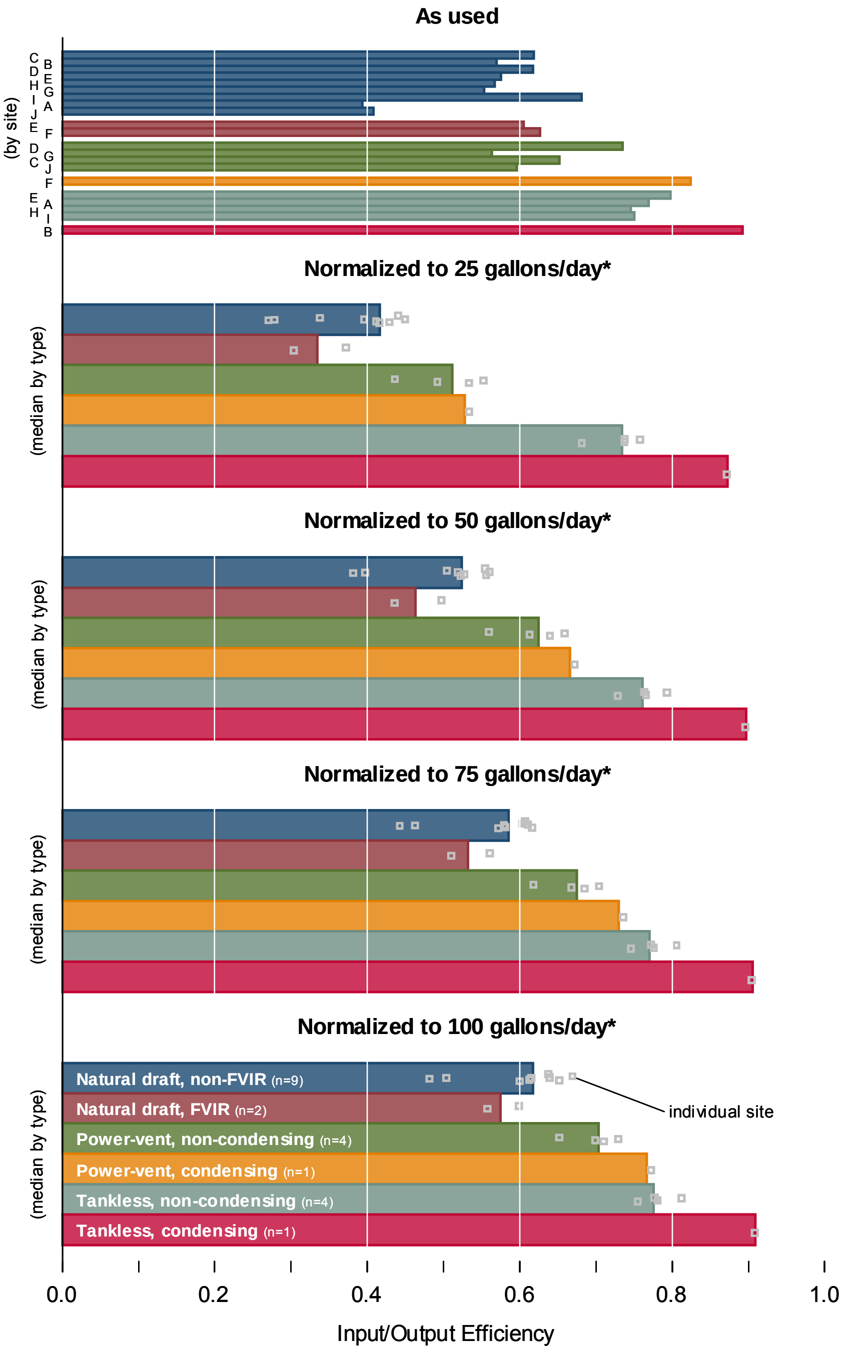
[17] Power-vent water heaters do experience off cycle losses via the flue, even with no standing pilot. Tank temperature and an open airflow path from the burner to the dilution air inlet allows stack flow through the flue into the room. We did not quantify this loss mechanism.

[18] Given that the actual gas input for a tankless system is exactly zero at zero load, use of a non-linear fit of input to output, with a zero intercept, may make sense from a theoretical perspective. We used a linear fit with a non-zero intercept, however, because if provides a good fit to the data across the practical range of water use encountered in our study.

This relationship can be seen in Figure 11, in which we plot the as-used input/output efficiencies of the water heaters in the study along with estimated efficiencies at normalized hot-water load levels. At any given hot-water load, the tankless water heaters have the highest efficiency, followed by the power-vented units, and lastly by the natural-draft water heaters. But the storage water heaters experience a significant drop-off in efficiency at low loads owing to their relatively constant standby losses, while the tankless units do not. All of this is a long way of saying that the savings for power-vent and tankless water heaters mainly arise from reducing relatively fixed standby losses—though to be sure, the two condensing water heaters in the study also provide inherently higher combustion efficiency.

FIGURE 11. INPUT/OUTPUT EFFICIENCY, AS-USED AND FOR NORMALIZED OUTPUT LOADS.



*60F cold-hot water temperature rise

Of course lower hot-water demand means lower water heating costs in general, so a given efficiency differential between two water heaters translates into fewer dollars of water heating savings. We turn next to an examination of water heater operating costs.

OPERATING COSTS

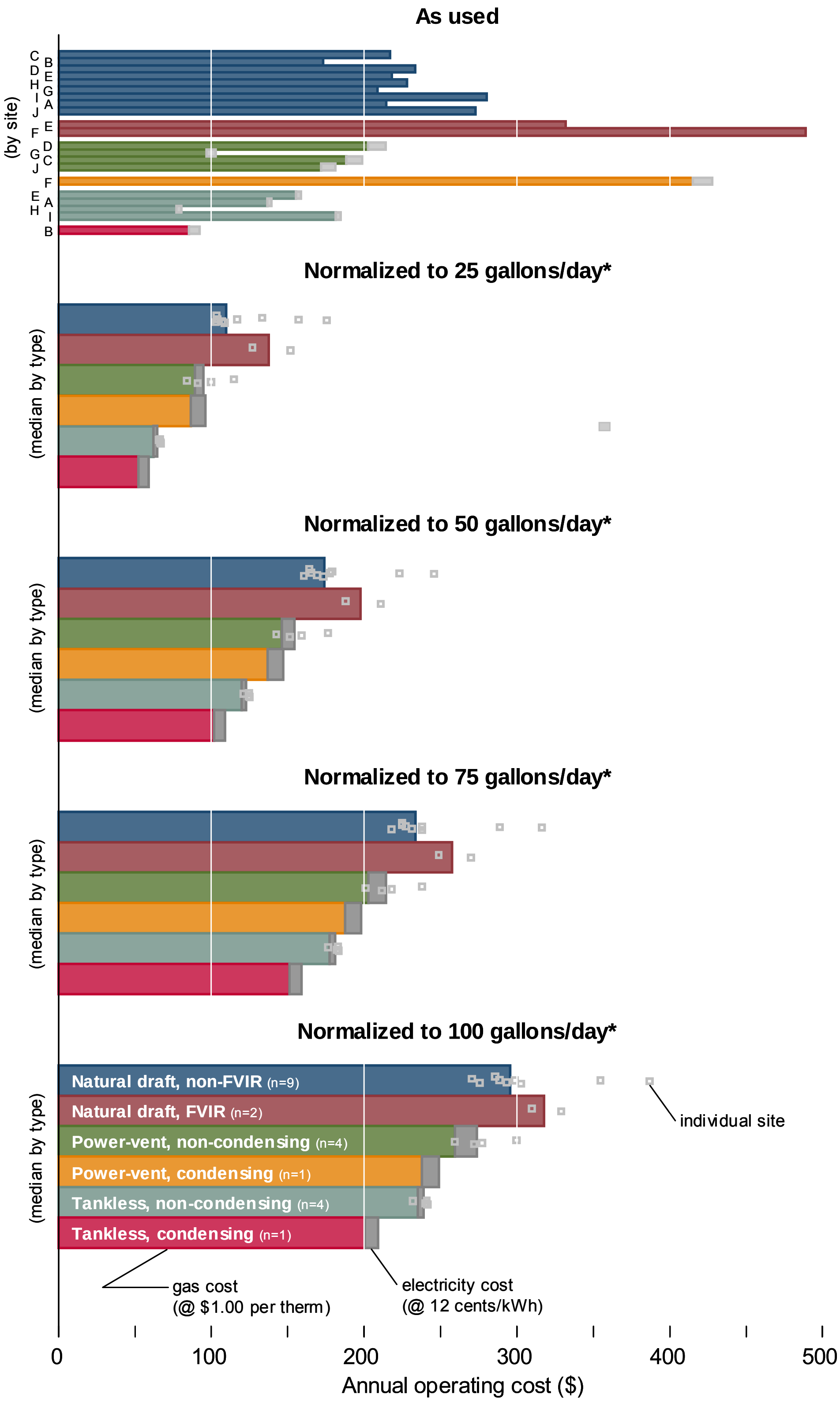
Figure 12 shows our estimates of annual operating costs for the water heaters in the study (including electricity costs for the power-vented and tankless models), and Table 4 summarizes the results in terms of medians by water heater type. The results suggest that a power-vent water heater will typically provide $20-25 in annual water heating cost savings, while a tankless water heater will save $50-60. Condensing versions of either of these will show generally higher savings, as well as provide more savings at higher hot-water loads. See Appendix E for estimated operating costs and efficiencies normalized to standard conditions for the individual water heaters monitored.

TABLE 4. TYPICAL ANNUAL OPERATING COSTS (AND SAVINGS).

		Hot-water use (gallons per day)*			
	Water heater type	25	50	75	100
Median annual operating cost	natural-draft (non-FVIR and FVIR)	$116	$176	$237	$298
	power-vent	$95	$154	$214	$274
	power-vent, condensing	$96	$147	$198	$249
	tankless	$65	$123	$181	$239
	tankless, condensing	$59	$109	$159	$209
Annual savings relative to natural-draft	power-vent	$21	$22	$23	$24
	power-vent, condensing	$20	$29	$39	$48
	tankless	$51	$54	$56	$59
	tankless, condensing	$57	$67	$78	$88
% savings	power-vent	18%	12%	10%	8%
	power-vent, condensing	21%	19%	18%	18%
	tankless	53%	36%	28%	24%
	tankless, condensing	87%	55%	43%	37%

*at 60F cold-hot water temperature rise

FIGURE 12. ESTIMATED ANNUAL OPERATING COSTS AT VARIOUS LOAD LEVELS.



*60F cold-hot water temperature rise

WATER HEATING DRAWS AND TEMPERATURE

Hot water consumption in study homes, averaged over the monitoring period for each water heater installed in each home, ranged from 27 to 139 gallons per day. We looked at hot water use in terms of draw "events." An event is an unbroken hot water draw over time; our specific definition is a period in which some hot water usage was observed during each five second monitoring interval. This definition means that a short pause in hot water use (of up to a few seconds) does not terminate the event.

Figure 13 shows the fraction of total hot water usage in each home in one gallon increments. A relatively large fraction of hot water use occurs in events of two gallons and less in many homes. There is additionally a spike in use at around 10 gallons in many homes; we believe these spikes to be associated primarily with showering. It is interesting to see events extending to 30 and more gallons in some homes. We believe such large volume events must be made up of multiple end uses (e.g. bathing, laundry, kitchen work) that overlap sufficiently so that no five-second period passes without some flow. Figure 14 shows this information in the form of cumulative fraction plots.

FIGURE 13. FRACTION OF TOTAL HOT WATER USAGE BY EVENT VOLUME FOR EACH WATER HEATER

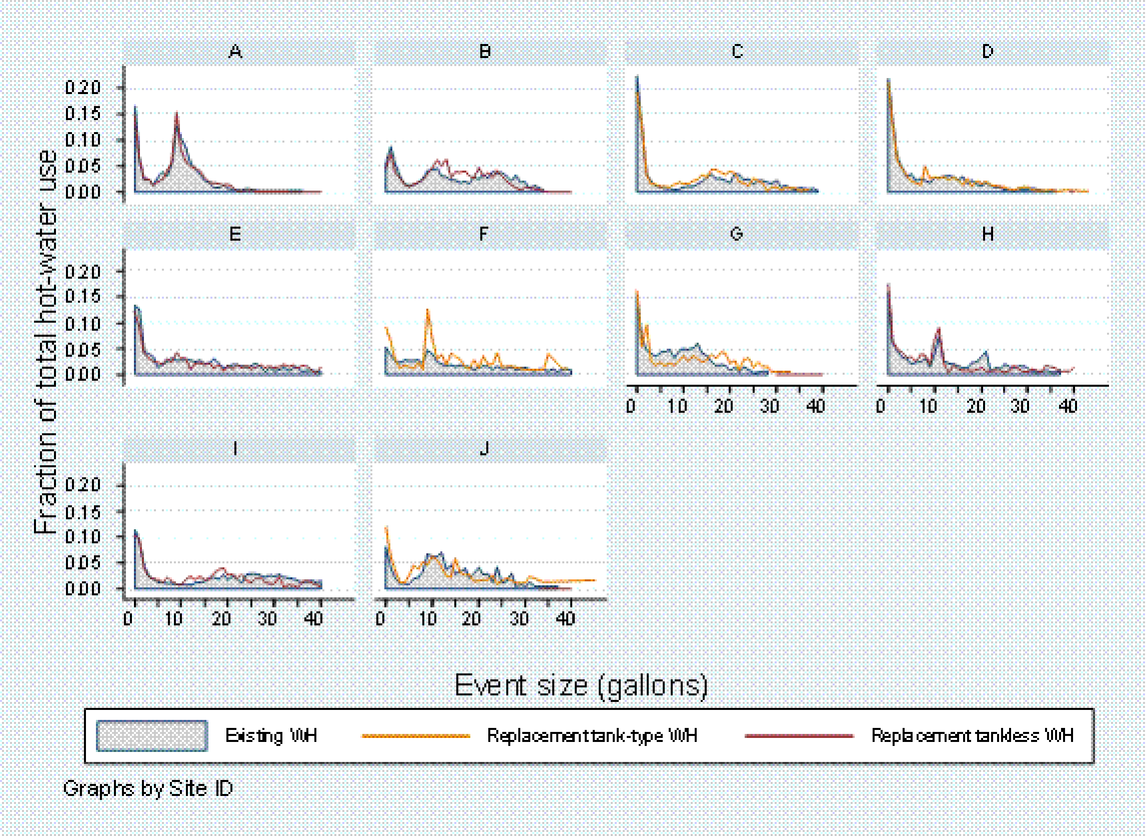


FIGURE 14. FRACTION OF TOTAL HOT WATER USAGE BY EVENT VOLUME FOR EACH WATER HEATER

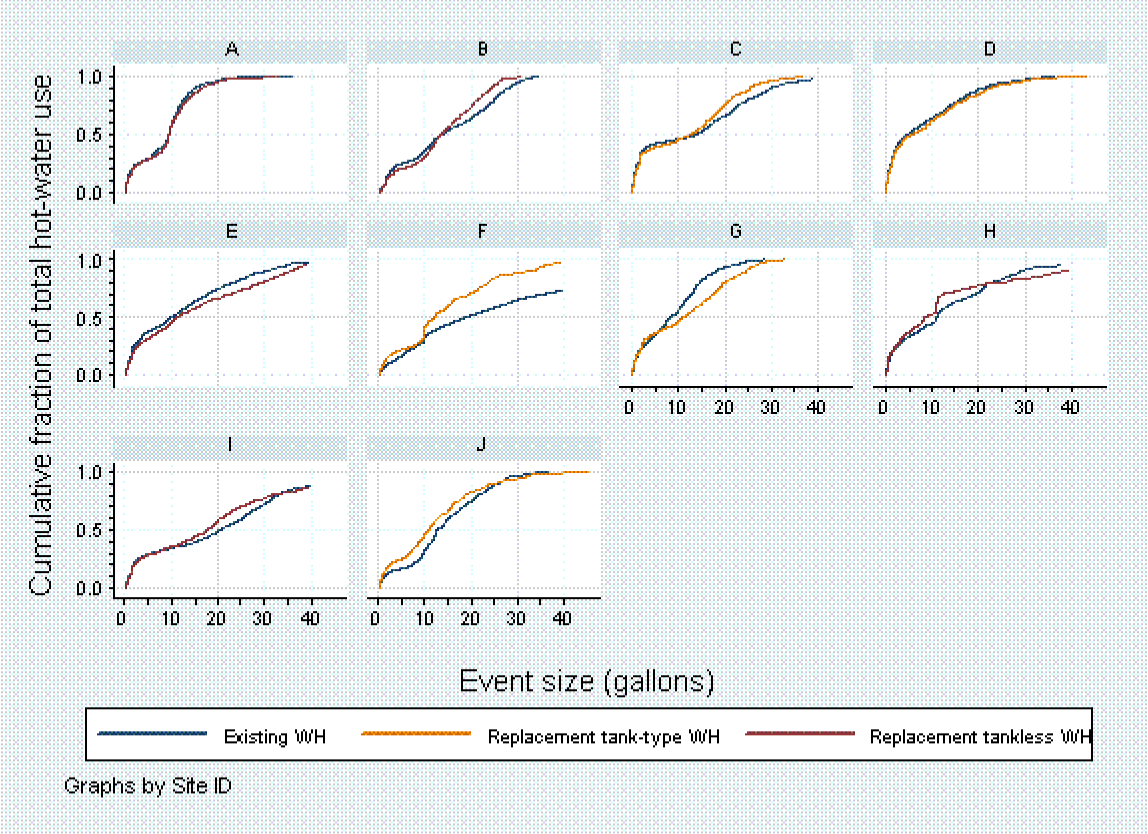


Figure 15 and Figure 16 show how the temperature of the hot water drawn from the water heater varies with cumulative draw gallon, as well as how individual draw events vary. The tankless water heaters (Figure 15) exhibit a short lag before they begin to deliver hot water, but then generally deliver a constant hot water temperature regardless of the amount of water drawn.

The storage water heaters begin to deliver hot water more quickly, but also show degradation in the hot water temperature well before draw volume equals the full storage capacity of the water heater. This is most pronounced at Sites J—where the temperature begins to decline almost immediately—and A, where there is a sharp temperature decline after an initial rise. A later autopsy of all the water heaters showed the dip tubes in these two tanks had disintegrated, encouraging the breakdown of temperature stratification and faster dropoff of delivery temperature. The very high temperature setting at Site J was probably the homeowners reponse to rapid temperature dropoff.

FIGURE 15. HOT WATER TEMPERATURE VERSUS CUMULATIVE GALLONS DRAWN (TANKLESS WATER HEATERS).

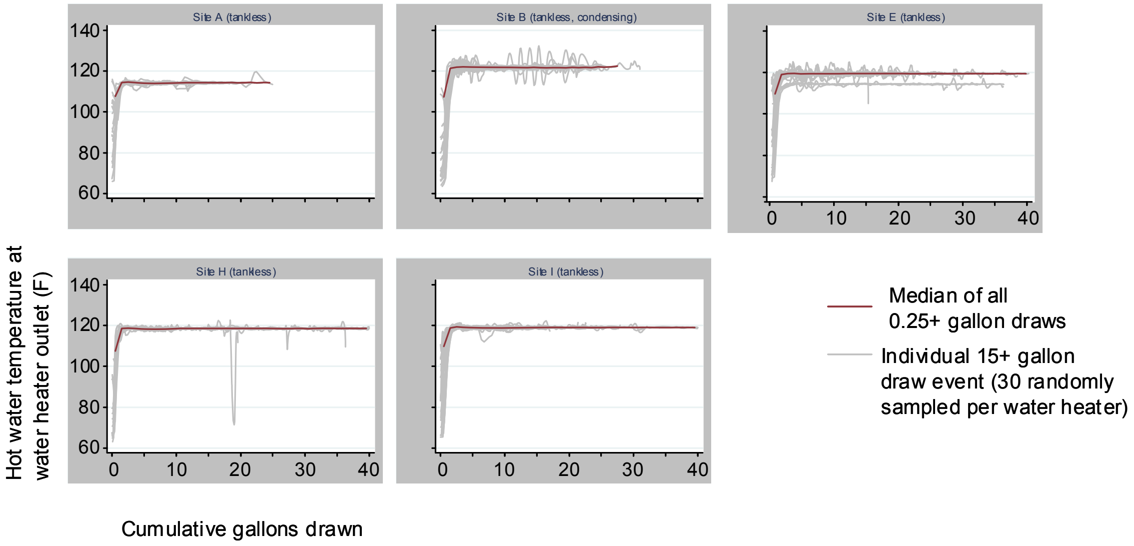
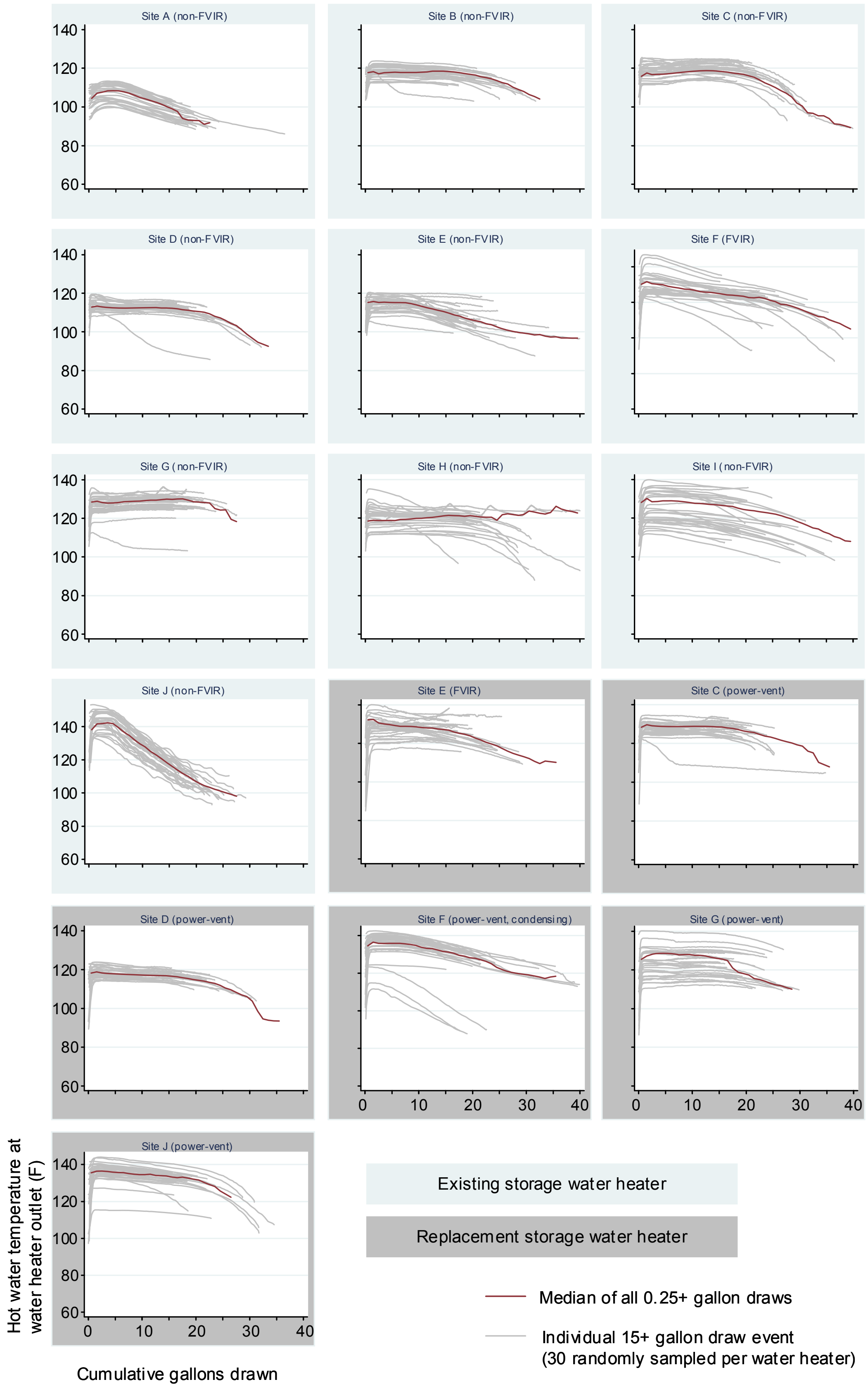


FIGURE 16. HOT WATER TEMPERATURE VERSUS CUMULATIVE GALLONS DRAWN (STORAGE WATER HEATERS).

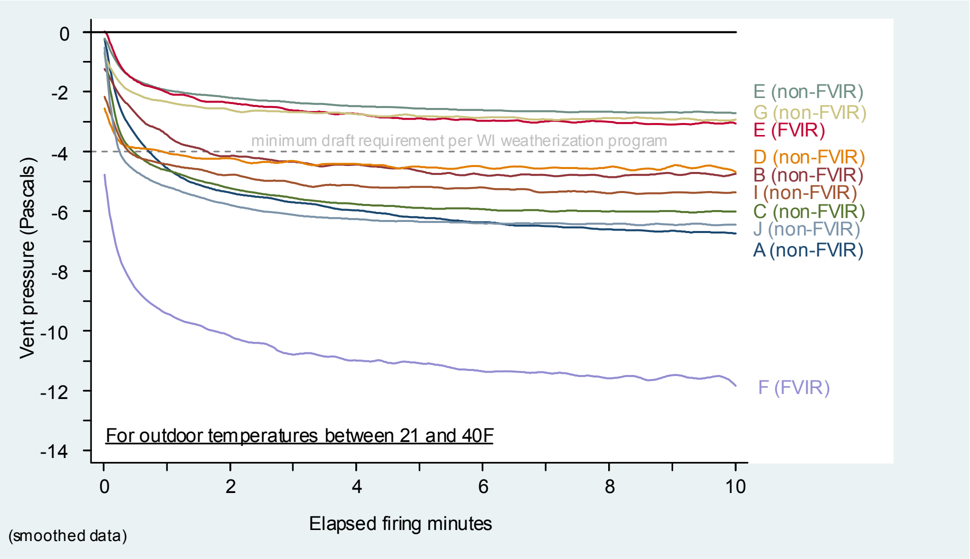


SPILLAGE AND BACKDRAFTING

Spillage of combustion products can occur with natural-draft devices if there is insufficient draft to remove combustion products from indoors, or if other devices (such as dryer or range hood) overpower natural draft forces and reverse the flow of combustion products. We monitored draft pressure in the vent system,[19] and also looked for signs of spillage of combustion products by monitoring CO_2 levels and temperature in the immediate vicinity of the draft diverter.

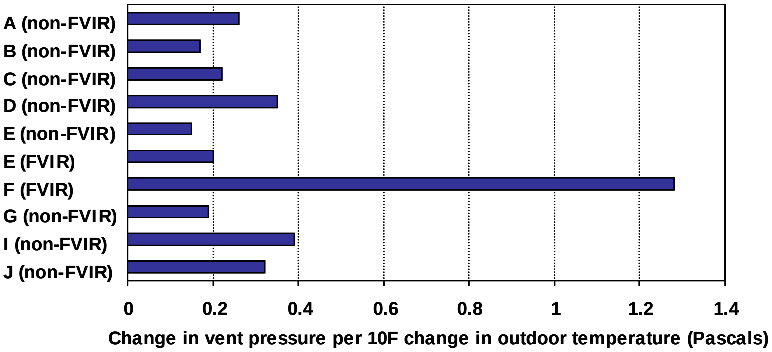
Vent Pressure

FIGURE 17, MEDIAN VENT PRESSURE VERSUS ELAPSED FIRING TIME FOR NATURAL-DRAFT WATER HEATERS.



As Figure 17 shows, most of the sites showed fully-developed draft pressures of 4-6 Pascals in moderately cold weather (21-40F). Sites E and G both had noticeably weaker draft pressures; in the former case, probably due at least in part to relatively short chimneys at these sites. These water heaters in fact do not meet the Wisconsin weatherization program standards for minimum acceptable draft pressure (4 Pascals) in this range of outdoor temperatures. Site F, on the other hand, exhibits very strong draft pressures owing to a tall chimney.

FIGURE 18. CHANGE IN STEADY-STATE VENT PRESSURE PER 10F CHANGE IN OUTDOOR TEMPERATURE.



Outdoor temperature strongly affects on-cycle draft pressure, due to the change in stack-effect with temperature. As Figure 18 shows, most sites exhibited an increase in

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[19] Note that the draft pressure we measured is the pressure drop from room air to a point in the vent system just beyond the draft hood. As such, it is essentially an indicator of the quantity and direction of flow through the vent system, and while it has some relationship to stack effect driving forces, it is not a direct measure of these forces. See also Appendix D.

draft pressure of 0.2 to 0.4 Pascals for every 10F decline of outdoor temperature—though Site F shows a much stronger reaction, again a function of a tall chimney that is sized to vent both the home's furnace and the water heater. Vent flows are relatively high at this site when the water heater operates alone and when it operates while the furnace is also on.

These results have implications for standards for minimum acceptable draft pressure. The Wisconsin weatherization program uses the values shown in Table 5 for determining whether a device such as a water heater has acceptable draft. The acceptable values in the table decline by 1 Pascal for every 20F change in outdoor temperature, or 0.5 Pascals per 10F change in outdoor temperature.

TABLE 5. WISCONSIN WEATHERIZATION PROGRAM REQUIREMENTS FOR MINIMUM ACCEPTABLE DRAFT FOR GAS APPLIANCES

Outdoor temperature range	Minimum Acceptable draft (Pa)
<20	-5
21-40	-4
41-60	-3
61-80	-2
>80	-1

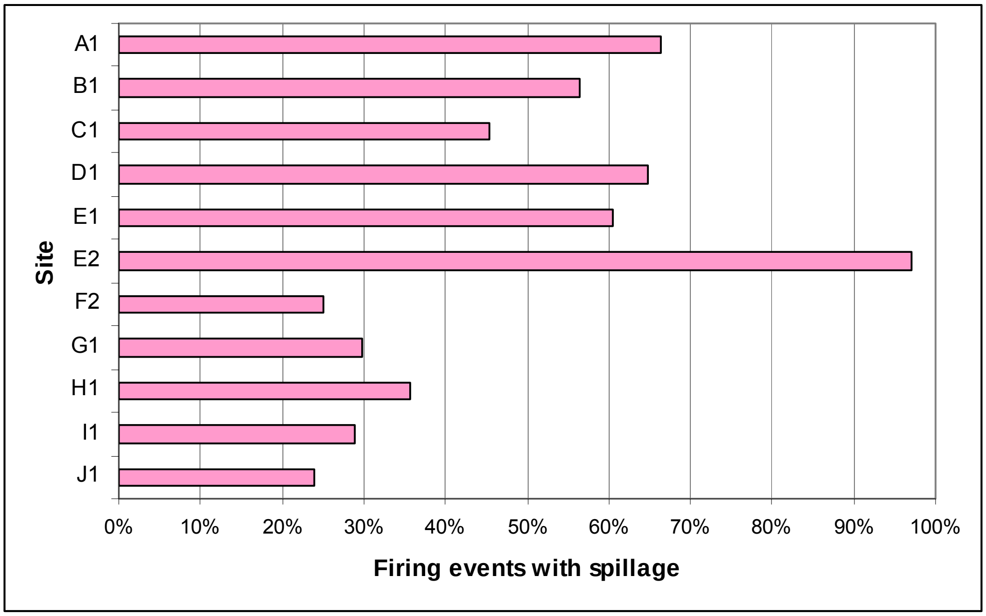
Because this change rate is significantly larger than all but one of our sites, sites that pass the draft requirement at one outdoor temperature range, can fail under other outdoor conditions. In particular, the water heaters at Sites E and G routinely fail the draft criterion under cold conditions, but pass in warm weather.

However, if the objective is to ensure at least 1 Pascal of draft in very warm weather, then our data suggest that Table 5 is conservative: i.e., it tends to fail some water heaters under cold conditions that still have acceptable draft in warm weather because their draft does not decline as rapidly in warm weather as the table would imply.

Spillage

CO_2 data showed that all of the natural-draft water heaters frequently spilled some combustion products at the start of a firing cycle, but then generally quickly developed sufficient draft to exhaust products for the remainder of the firing cycle. The incidence of detectable spillage on burner start ranged from about 25 to about 95 percent across the systems investigated (see Figure 19). We used a measured CO_2 level of 1000 ppm above the pre-firing background room level as an indicator of spillage. Inspection of the detailed patterns of spillage events showed that significant spillage could also be identified by elevated temperature above the draft hood, but temperature is a more ambiguous signal of spillage because the temperature in the vicinity of the vent increases somewhat during burner operation even in the absence of spillage.[20]

FIGURE 19. INCIDENCE OF DETECTABLE COMBUSTION PRODUCTS SPILLAGE WITHIN 5 MINUTES OF MAIN BURNER IGNITION



We also identified about 30 instances of spillage, identified by CO_2 elevation, beyond the first five minutes of main burner operation. Most of these were of relatively short duration—and many appeared to have been caused by gusty winds, as evidenced by brief vent pressure reversals.[21] But several were sustained. Figure 20 shows three of the six significant spillage events where we recorded a vent pressure

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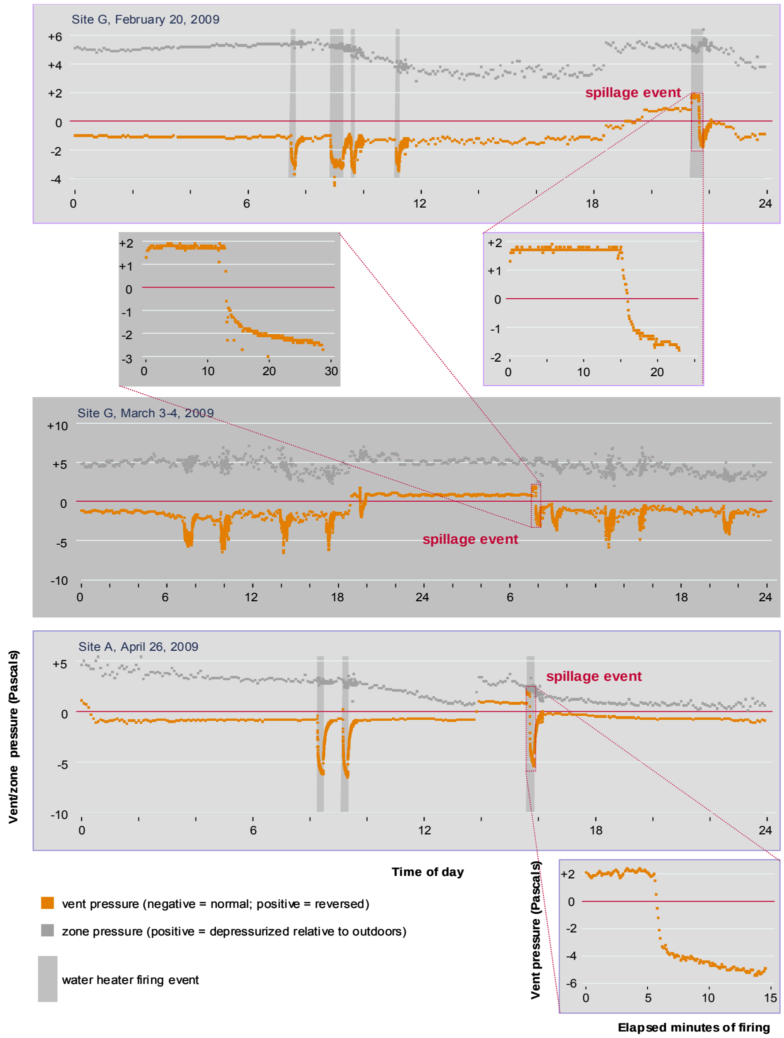
[20] Spillage on burner start is also sometimes associated with a brief reversal of normal vent pressure, i.e. vent pressure becomes greater than room pressure. We believe this may be due to dynamic effects as flow in the vent system increases, specifically that the momentum of the combustion products exiting the water heater flue causes a brief pressure increase in the vent. Such observations do not appear to indicate actual reversal of flow in the venting system.

[21] The monitoring system recorded about 100 firing events (across all water heaters) that showed at least a brief period of positive vent pressure after the first 5 minutes of operation. In most cases, we did not observe a significant elevation in ambient CO_2 associated with these pressure events.

reversal of more than one minute. In all cases here (though not for all six events), vent flow was reversed for at least several hours prior to the spillage event. These episodes of prolonged pressure reversal appear to indicate sustained downdrafting through the venting system.[22] Five of the six sustained spillage events (and 12 of 30 total post-startup spillage events that we identified) occurred at Site G, while the sixth event occurred at Site A (see Figure 20).

In all of these cases, there is an increase in the pressure difference between the basement and outdoors, with the basement moving to a lower pressure relative to outdoors, near the time when downdrafting begins. In two of the cases, the pressure change is quite sharp. This pressure change is likely a contributing factor in the development of downdrafting in these episodes, although other factors must be present, as similar depressurization of the basements at other times did not trigger downdrafting. As mentioned earlier, Site G has a relatively short chimney (the shortest of any included in the study), which contributes to low natural-draft pressures which are more easily overcome. The chimney at Site A is longer than those at several other sites that did not experience a similar pattern of downdrafting, and we do not have confidence in any specific causal factors for this episode.

FIGURE 20. THREE SPILLAGE EVENTS AT SITES G AND A.



We also reviewed the data for other instances of apparent downdrafting that may have developed during off cycle operation, but not carried over to a main burner event. As an indicator of such flow reversal, we looked for cases in which, during a 5-minute off cycle data collection period, vent pressure remained positive (opposite of normal) for at

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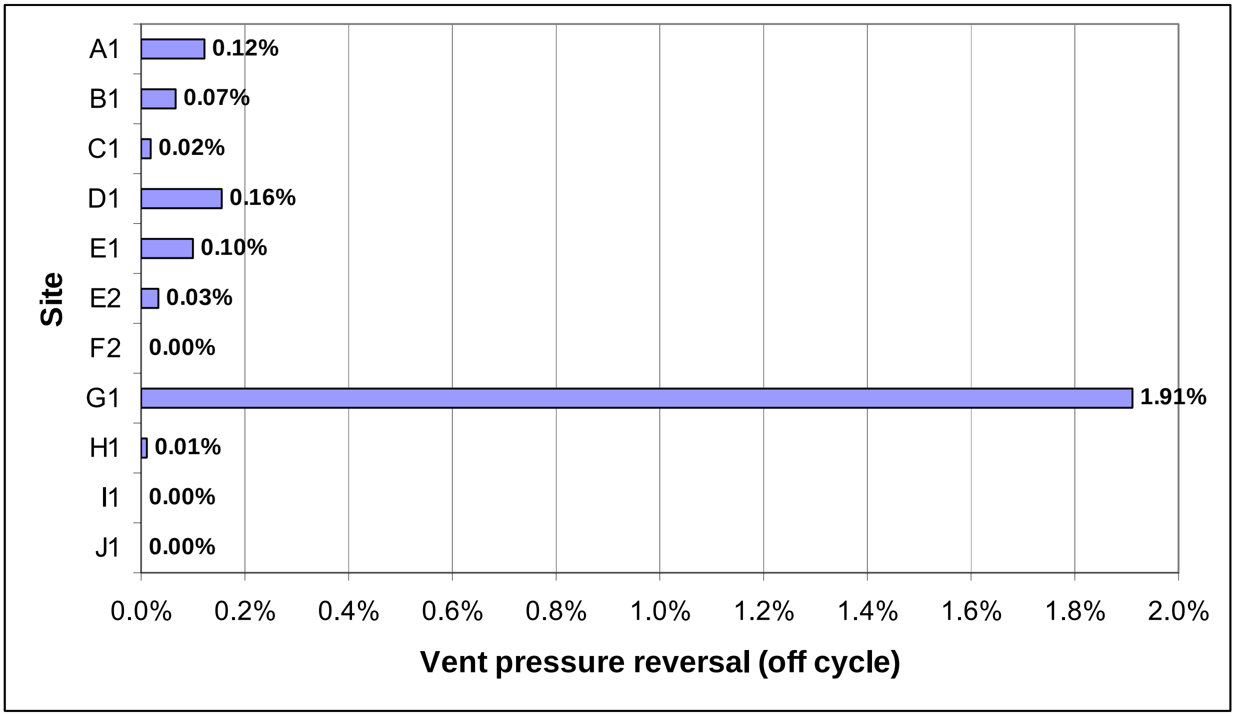
[22] Sustained downflow occurs when the chimney fills with cooler outdoor air, negating the usual upward stack effect driving force, in combination with depressurization of the basement (or combustion appliance zone in more general terms).

least 90% of the observations. This is intended to isolate cases in which flow has truly reversed, while allowing for cases in which gusty winds lead to some observations of the opposite sign. Such full reversals occur more frequently than we expected, though at most sites the frequency is far less than one percent of observations. Site G, however, where all the most serious venting problems occurred, had vent pressure reversals in nearly two percent of all off cycle operation (see Figure 21)

FIGURE 21. INCIDENCE OF POSITIVE VENT PRESSURE DURING WATER HEATER OFF CYCLE



APPENDIX A — SITE AND WATER HEATER CHARACTERISTICS

The homes in the study are all wood frame homes with full basements, typical of homes in the Upper Midwest. In every case, existing and replacement water heaters were installed in basements. One basement (Site B) has one fully exposed wall and a door to the outside, while all other homes have basements fully below grade on all sides.

There were several changes in occupancy in study homes, with children and parents moving in and out in several cases, and one home (Site G) being sold, with a single person replacing the couple who had occupied the home (in July, 2009).

TABLE 6. OPERATING PROFILES OF WATER HEATERS AS TESTED

Site	Existing / Replacement	Type	Mean water inlet temp (F)	Mean water outlet temp (F)	Mean daily gallons	Mean daily firing events	Mean daily water draw events	Mean daily input therms	Mean daily output therms	Overall thermal efficiency	Mean daily kWh	Total days of data
A	Existing	Non-FVIR	57.8	104.7	55.6	2.9	49.1	0.587	0.227	38.7%	0.000	250
A	Replacement	Tankless	59.5	105.6	67.9	46.5	53.9	0.374	0.286	76.6%	0.062	215
B	Existing	Non-FVIR	58.2	117.1	53.8	2.8	20.9	0.474	0.268	56.7%	0.000	368
B	Replacement	condensing tankless	61.1	117.3	43.8	11.6	13.2	0.233	0.208	89.2%	0.166	111
C	Existing	Non-FVIR	55.3	114.8	72.7	4.8	102.6	0.594	0.367	61.8%	0.000	275
C	Replacement	Power -vent	57.8	127.4	57.5	7.0	59.1	0.516	0.336	65.2%	0.236	209
D	Existing	Non-FVIR	55.4	112.0	82.2	5.7	94.9	0.639	0.391	61.3%	0.000	281
D	Replacement	Power -vent	59.4	117.1	82.1	8.4	91.1	0.555	0.397	71.5%	0.259	221
E	Existing	Non-FVIR	60.8	112.9	78.3	6.3	63.4	0.597	0.343	57.5%	0.000	244
E	Replacement (short-term)	FVIR	58.8	129.0	93.5	8.2	73.9	0.909	0.550	60.5%	0.000	76
E	Replacement	Tankless	64.6	113.1	80.4	47.7	58.1	0.425	0.340	79.8%	0.069	177
F	Existing	FVIR	47.9	126.1	127.3	6.6	85.8	1.339	0.839	62.7%	0.000	159
F	Replacement	Condensing power-vent	50.0	131.0	138.6	8.9	70.8	1.137	0.937	82.4%	0.290	22
G	Existing	Non-FVIR	55.6	127.4	52.9	5.6	46.9	0.571	0.316	55.3%	0.000	142
G	Replacement	Power -vent	58.9	123.8	27.5	4.5	28.3	0.265	0.149	56.3%	0.136	204
H	Existing	Non-FVIR	60.3	117.3	74.2	7.7	50.4	0.624	0.354	56.7%	0.000	79
H	Replacement	Tankless	63.3	97.4	43.5	19.2	26.7	0.212	0.158	74.5%	0.072	169
I	Existing	Non-FVIR	54.0	128.1	84.1	3.9	58.0	0.767	0.523	68.1%	0.000	149
I	Replacement	Tankless	58.5	113.4	79.7	36.1	42.9	0.497	0.373	75.0%	0.073	216
J	Existing	Non-FVIR	52.1	131.1	45.1	3.5	25.9	0.748	0.303	40.5%	0.000	149
J	Replacement	Power-vent	61.0	132.6	43.3	6.0	36.2	0.470	0.266	56.5%	0.212	58

TABLE 7. WATER HEATER CHARACTERISTICS

Site and water heater type[23]	Orig / Repl	Type	Tank Size (gal)	Nameplate Input (Btu/hr)	Measured Input (Btu/hr)	Measured Pilot Light Input (Btu/hr)	Year of mfr	Vent size at draft hood (in)	Chimney Height (ft) (Natural draft only)	Chimney shared with heating appliance?
A1	Orig	Natural-draft	50	50,000	50,562	1,083	1977	4	23	No
B1	Orig	Natural-draft	40	40,000	36,986	371	1998	3	18	No
C1	Orig	Natural-draft	40	38,000	33,451	336	2000	3	18	No
D1	Orig	Natural-draft	40	34,000	30,751	432	1993	4	18	Furnace
E1	Orig	Natural-draft	40	35,500	29,818	263	1991	3	22	No
F2	Orig	Natural-draft (FVIR)	50	40,000	34,942	437	2003	3	27	Furnace
G1	Orig	Natural-draft	40	34,000	29,958	381	1993	3	17	No
H1	Orig	Natural-draft	40	37,000	32,927	351	1991	3	21	Boiler
I1	Orig	Natural-draft	40	40,000	35,072	749	1992	3	18	No
J1	Orig	Natural-draft	40	40,000	34,783	537	1986	3	27	No
A5	Repl	Tankless	N/A	199,000 (max)		N/A	2009	N/A	N/A	N/A
B6	Repl	Tankless (condensing)	N/A	175,000 (max)		N/A	2009	N/A	N/A	N/A
C3	Repl	Power-vent	40	40,000	39,610	N/A	2009	N/A	N/A	N/A
D3	Repl	Power-vent	40	40,000	38,780	N/A	2009	N/A	N/A	N/A

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[23] The number following the site ID refers to the water heater type 1=conventional natural draft, 2=FVIR natural-draft, 3=power vent, 4=condensing power vent, 5=tankless, 6=condensing tankless

Site and water heater type[23]	Orig / Repl	Type	Tank Size (gal)	Nameplate Input (Btu/hr)	Measured Input (Btu/hr)	Measured Pilot Light Input (Btu/hr)	Year of mfr	Vent size at draft hood (in)	Chimney Height (ft) (Natural draft only)	Chimney shared with heating appliance?
E2	Repl (short-term)	Natural-draft (FVIR)	40	40,000	32,215	256	2009	3		No
E5	Repl	Tankless	N/A	199,000 (max)		N/A	2009	N/A	N/A	N/A
F4	Repl	Power-vent (condensing)	50	76,000	65,420	N/A	2009	N/A	N/A	N/A
G3	Repl	Power Vent	40	40,000	37,850	N/A	2009	N/A	N/A	N/A
H5	Repl	Tankless	N/A	199,000 (max)		N/A	2009	N/A	N/A	N/A
I5	Repl	Tankless	N/A	199,000 (max)		N/A	2009	N/A	N/A	N/A
J3	Repl	Power-vent	40	40,000	40,170	N/A	2009	N/A	N/A	N/A

APPENDIX B — MONITORING DETAILS

DATA COLLECTION AND ANALYTIC METHODS

The monitoring system developed for this project was based on a single-board computer (MicroSys model SBC2596). This board has 32 channels of analog input capability, individually configurable as single ended or differential measurement channels, as well as several modes of digital input and outputs usable for status monitoring and control. Sensors and transducers were selected to meet the measurement and analysis objectives, as summarized in Table 2 in the main report. Sensors and transducers as used are described in Table 8.

TABLE 8. WATER HEATER MONITORING SYSTEM SENSORS AND TRANSDUCERS

Measured Parameter	Sensor or Transducer	Technology	Estimated Effective Accuracy[24]
Pressure difference (vent – zone, outdoor – zone)	Setra model 264 +/- 62 Pa range	Capacitive	+/- 3% of reading
CO_2 (Room high, room low, vent, flue)	Digital Control Systems model 305E	NDIR	
CO (Room high, room low, vent, flue)	Figaro model TGS 5042	Electrochemical	+/- 20% of reading
Oxygen	Honeywell model GMS-10RVS 0-250 mbar range	Catalyzed zirconia	+/- 3 mbar
Temperature (Room high, room low, vent, outdoor)	Custom packaged 10K ohm thermistors	Thernistor	+/- 0.4 F
Water draws	Badger model 25 water meters fitted with magnetically activated pulse output device	Nutating disk meters, AWWA design	+/- 1% of flow
Gas flow (tankless units)	American AC-250, IMAC high resolution pulser	Positive displacement diaphragm	+/- 2%
Gas valve status (natural-draft and power-vent units)	Gas pressure switches		Very small
Status of furnace gas, furnace blower, and dryer (when accessible)	Current sensor		Very small

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[24] Estimated effective accuracy refers to the expected error generated in results generated through the use of this sensor or transducer. When differences are evaluated, e.g. gas concentration differences between room and vent, repeatability is used in this estimate, when absolute values are of interest, accuracy is used. Includes estimated accuracy of analog to digital conversion at single board computer. Accuracy values don't apply to those cases where installation or operating problems occurred.

We used a shared-sensor approach for CO_2, CO, and differential pressure measurements. For the differential pressure measurement a single pressure transducer was connected via three valves to measure vent-room differential pressure, outdoor-room pressure, and a zero offset was measured every three minutes by connecting the two pressure lines together.

A single CO_2 sensor and CO sensor, both designed for pumped sampling, were mounted in the main cabinet of each system, connected through a pump to four valves. The valves, controlled by the operating program, were activated to select from four sampling locations.

The CO_2 sensor was selected to provide reasonable measurement resolution during pilot-only operation, and had an upper measurement limit of 5000 ppm. This meant it would be off scale whenever the main burner was fired, so the CO_2 and CO sensors were controlled to observe room air only during main burner firing. The use of a shared sensor for all CO_2 measurements has the benefit of reducing errors in the differences between room air and combustion products; the difference between room and vent will drift much less than any absolute change in sensor calibration point over time. Since the calculation vent flow using stoichiometry is sensitive primarily to the difference in CO_2 concentration from room to vent system, this reduction in error has real value.

We used measured oxygen levels as a basis for stoichiometric calculation of vent flow during main burner operation, mirroring the use of CO_2 for measuring off cycle flow. For cost reasons, we purchased just two oxygen sensors, and rotated them among the sites over the period of the project.[25]

The core monitoring system, including the single board computer, pressure transducer, CO and CO_2 transducers, sampling pump, valving for both gas sampling and pressure measurement, along with various signal conditioning electronics and connectors, was mounted in a cabinet at each site, typically several feet away from the water heater.

Gas sampling was done via plastic tubing, with copper sampling tubes inserted into the water heater vent connector and flue pipe for sampling from those locations. Temperature and gas concentration measurements near the water heater draft hood had multiple purposes, including background levels of CO_2 for use in stoichiometric flow calculations, inlet air temperature for use in calculation of thermal efficiency, and for observation of both CO_2 elevation and temperature elevation that would indicate combustion products spillage. To capture warm combustion products that might flow from the draft hood, we fabricated open rings of soft copper tubing with a number of small holes drilled to take in air around the circumference of the vent pipe.

We used pressure activated switches mounted on the gas pressure test port on the gas valves to monitor burner status on natural-draft and power-vent water heaters, and installed gas meters with pulse outputs to measure gas input to the tankless systems.

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[25] We considered a number of alternative methods for measuring vent flows, including temperature drop longitudinally in the vent, calibration of vent pressure drop using an orifice device or “duct blaster,” injection and concentration measurement of a tracer gas, and velocity measurement using a pitot tube or hotwire anemometer.

Carbon dioxide concentrations were used as the basic measured input to calculate total volumetric flow through the venting system, based on knowledge of the chemistry of the fuel and combustion air, and the fuel flow rate.

Two oxygen sensors, responsive to oxygen concentrations from 0 to 25 percent, were rotated among the sites and used for combustion products measurement during main burner operation.

Pilot light gas input rate was a significant parameter in analysis of vent flows. Our general approach to measuring pilot gas flow rates was to mount a webcam focused on the main house gas meter, connected to a laptop computer and set up to record a picture every 20 to 30 seconds over a period of a few days, then review the photos to determine the flow rate. Because standard gas meters show cyclical non-uniformities in output over full cycles of their dial indicators, we sought to analyze full revolutions of the 1 or 2 cubic foot dial present on most meters. This meant looking for periods of up to about six hours with no gas draw other than the water heater pilot light. Fortunately, most of the study homes had no gas appliances other than the water heater and furnace or boiler. By doing this data collection in spring weather, we were able to capture adequate data.

Pilot light gas flow is not regulated at water heaters, and varies with gas line pressure, which in turn is affected by heating system operation. To adjust for the effect of furnace operation on pilot gas flow, we monitored gas line pressure at the water heaters while gathering pilot flow data, and calculated a reduced pilot light input rate for periods of furnace gas flow. This correction is typically about five percent of pilot flow.

We obtained water heater main burner gas flow rates either from webcam photos, or where webcams were not deployed (e.g. power-vent water heaters), from direct clocking of the gas meter with a stopwatch.

We assumed that, for fixed-input natural-draft and power-vent water heaters, main burner gas input would be constant over time. Water heater gas valves incorporate a simple pressure regulator intended to reduce the effects of pressure variation in the gas line, and some short-term observations showed little variation with line pressure fluctuations associated with furnace operation.

We purchased water meters meeting American Water Works Association standards for cold water metering, and fitted them with magnetically activated solid state switching devices to provide a pulse output at a rate of about 100 pulses per gallon. The pulses were counted directly on the single board computer.

Our water meters, custom-fitted with electronic output devices, did not produce a completely reliable indication of positive hot water flow. In particular, we became suspicious of recorded pulses that appeared as single or double pulses in a five second period, nominally indicating a trickle of hot water draw. We found they fell into two patterns. One of these was actual hot water consumption at a low rate, exemplified by leakage and by the water supply to a humidifier on a forced air furnace. The other pattern consisted of pulses that were not associated with a positive water draw. We believe these pulses appear when water pressure changes act against air trapped in the system, moving water in one direction or the other through the meter, and sometimes cycling repeatedly in both directions, thus generating pulses with little or no net flow. We were able to distinguish these patterns by inspecting water line temperatures associated with apparent flow.

The monitoring system executed a scan of all input channels once each second. A new data record for water heater operation and combustion products measurement was saved each five seconds during main burner firing (and including a cool down period of several minutes after firing), and each five minutes at other times. Hot water usage data was recorded for every five-second interval in which any water meter pulses were detected. We also occasionally set each system to record all data on a one-second basis in order to obtain some high-resolution data for each site.

The data recorded by the monitoring system proved to be of generally good quality; however, it was far from complete at many sites. Installation errors in crossing gas sampling and pressure lines caused some loss of data. Several incidents of accidental breakage of gas pressure switches resulted in lost water heater operating data. Condensation in the tube that provided the outdoor pressure signal caused a loss of some zone pressure data. The pulse-output gas meters used at tankless water heater sites suffered from failures in three cases and had to be returned to the factory for repair. And the single board computers themselves were susceptible to crashing for reasons that we never completely diagnosed.

APPENDIX C — VENT FLOW AND INFILTRATION LOAD ESTIMATE CALCULATION PROCEDURES

This appendix documents how we developed our estimates of vent-system flow and infiltration load estimates for the existing natural-draft water heaters at the 10 sites. A number of steps were involved, but these can be broadly characterized as follows:

- Use measured CO_2 and O_2 levels in the vent system with stoichiometric calculations to estimate vent-system flow, and relate this to measured static pressure in the vent system.
- Use vent-system static pressure to estimate vent flow across all data.
- Model daily vent flow (by operating mode) as a function of outdoor temperature.
- Develop models of water heater and (for shared-flue systems) heating system operating time.
- Combine the above with temperature bin data and certain assumptions to estimate seasonal infiltration impacts.

MEASURING VENT FLOW

Our primary measurement of vent flow comes from the fact that combustion at the water heater pilot increases the CO_2 concentration in the vent system over ambient levels. If the flow rate and composition of the gas to the pilot are known (more on this later), then stoichiometry can be used to translate a measured CO_2 elevation into mass flow in the vent system.

Our monitoring system was set to sample CO_2 concentration among four locations when the water heater was not firing: (1) inside the water heater flue; (2) in the vent system above the draft diverter; (3) ambient conditions at the top of the water heater; and, (4) ambient conditions at the bottom of the water heater.[26] The fact that ambient air can enter the vent system in two locations—and that the CO_2 levels at these locations are not always the same—complicates the situation somewhat. We used the following procedure:

1. Calculate an approximate fraction of vent flow above the draft diverter that derives from flow through the water heater flue using the ratio of vent system CO_2 elevation and water heater flue CO_2 elevation, in both cases calculated relative to the ambient-high location.
2. Get a weighted average of ambient-high and ambient-low CO_2 values.
3. Calculate vent flow (above the draft diverter) based on measure vent CO_2 elevation above the weighted average ambient value.

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[26] Note that we used a pumping arrangement to measure CO_2 concentration levels at all four locations using a single sensor: this eliminated concerns about errors from instrument drift that might arise from deriving CO_2 elevation from measurements made with multiple sensors.

As noted above, the translation of CO_2 elevation to mass flow requires knowledge of gas flow rate and the composition of the natural gas that is combusted. For the former, we relied on each home's revenue gas meter for one-time measurements of pilot flow. Because pilot flow rate is very low, we installed a time lapse camera on each home's gas meter to record the dial positions over a period of several days. From these data, we were generally able to extract at least one (and sometimes several) periods of six to eight hours when the water heater pilot was the only device drawing gas, from which we could get a reasonably accurate measurement of pilot flow. We also used the time-lapse data to get several measurements of water heater main-burner flow.

One other minor pilot gas-flow correction was also necessary. We determined that the pilots for the water heaters (unlike flow to the main burner) are not pressure-regulated. We also determined that gas flow to the furnace when it was firing reduced the pressure in the gas line slightly. We used one-time measurements of gas pressure with and without furnace operation to estimate a slightly reduced pilot flow rate to the water heater, and used a weighted average of these two values for periods when the furnace operated.

Table 9 summarizes the various gas flow measurements.

TABLE 9. MEASURED GAS FLOW RATES.

	Pilot gas flow (cubic feet per hour)		
Site	*As measured*	*Adjusted for furnace operation*	**Main Burner gas flow** (cubic feet per hour)
A	1.082	1.054	50.56
B	0.371	0.421	36.99
C	0.336	0.327	33.45
D	0.431	0.418	30.75
E (non-FVIR)	0.358	0.353	29.82
E (FVIR)	0.351	0.346	32.21
F	0.437	0.422	34.94
G	0.381	0.379	29.96
H	0.351	0.335	32.93
I	0.749	0.731	35.07
J	0.537	0.516	34.78

Gas composition is also a factor in being able to apply stoichiometry to estimate vent flow. We used typical values for natural gas in the area shown in Table 10 that we obtained from the local gas utility. From our discussions with utility staff, we believe that the composition of natural gas delivered to this area is fairly stable. A Monte Carlo analysis using likely ranges for the constituents of natural gas in the area suggests that uncertainty in gas composition creates only about a six percent uncertainty in vent flow.

TABLE 10. TYPICAL COMPOSITION OF NATURAL GAS IN MADISON, WI

Methane	94.00%
Ethane	2.60%
Propane	0.40%
Butane	0.07%
Pentane	0.06%
Hexane +	0.02%
CO_2	0.95%
Other	1.91%
Total	100.00%

Source: personal communication with John Kilsdonk, Madison Gas & Electric Company, February 19, 2009.

In addition to calculating vent flow based on pilot stoichiometry we were also able to get measurements of on-cycle vent flow from measured vent-system O_2 levels and main-burner stoichiometry. The process is similar to that for the off-cycle calculations, except that because combustion uses up oxygen, we based the calculations on the oxygen depletion between the ambient air and the combustion products in the vent system.[27]

We had much less data for on-cycle vent-flow analysis than for off-cycle analysis for two reasons,. First water heaters typically fire less than 10 percent of the time, so they simply spend far more time in off-cycle mode.[28] Second, although we were able to continuously monitor CO_2 with a dedicated sensor at each site, the oxygen sensors were too expensive for this: instead, we rotated two sensors among all the sites.

Nonetheless, we were able to obtain on-cycle vent-flow data across a range of flows for most sites, which we used as a semi-independent cross-check against our off-cycle measurements. In both cases, our goal

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[27] We did not directly measure ambient oxygen levels at the sites. However we did record oxygen levels in the vent system during pilot operation during times when we were also able to calculate off-cycle vent flow from CO_2 data. We used the off-cycle data to estimate the (slight) oxygen depletion from pilot combustion, and then estimated daily values of ambient oxygen levels. We used this process mainly to account for sensor drift, since actual ambient oxygen is unlikely to be much below the typical value of 20.9 percent.

[28] Also, we dropped the first two minutes of each firing cycle, when there is much instability in the vent system.

was to relate stoichiometrically-derived estimates of vent system flow to static pressure in the vent system, for which we had data across a wide range of conditions.

In all cases, we found a strong linear relationship between calculated vent flow and the square root of vent-system static pressure, as one would expect from turbulent orifice flow (Figure 22). Theoretically, the on- and off-cycle measurements should fall along a common line that goes through the origin.[29] However, we discovered that thermal gradients in the tubing used for the pressure measurements created small baseline pressures that effectively reduce the measured pressure drop slightly, thus shifting the data to the left a bit. Moreover—because this effect is rooted in the fact that the end of the pressure tubing that is inserted in the water heater's venting system is warmer than the other end—when the water fires, the magnitude of the effect is larger. Because of this, we used the on-cycle regression fits for periods when the water heater was firing, and used the off-cycle fits for other periods.

Note also that the regression equations shown in Figure 22 actually predict the (standard) volumetric flow rate of combustion products, not just the amount of air flowing through the system. But for natural gas combustion, the cfm of combustion products is very close to the cfm of air plus the cfm of natural gas: it was therefore a simple matter of deducting either the pilot or main burner+pilot gas flow rates to the regression-based values to arrive at airflow.

We applied the regression equations shown in Figure 22 to the vent-system static pressure data (corrected for temperature-dependent density differences) collected over all time periods, and then calculated daily average vent-system airflow estimates by operating mode. The regression equations actually predict the flow rate of combustion products

The next task was to model daily vent flow as a function of other parameters to get monthly and seasonal averages.

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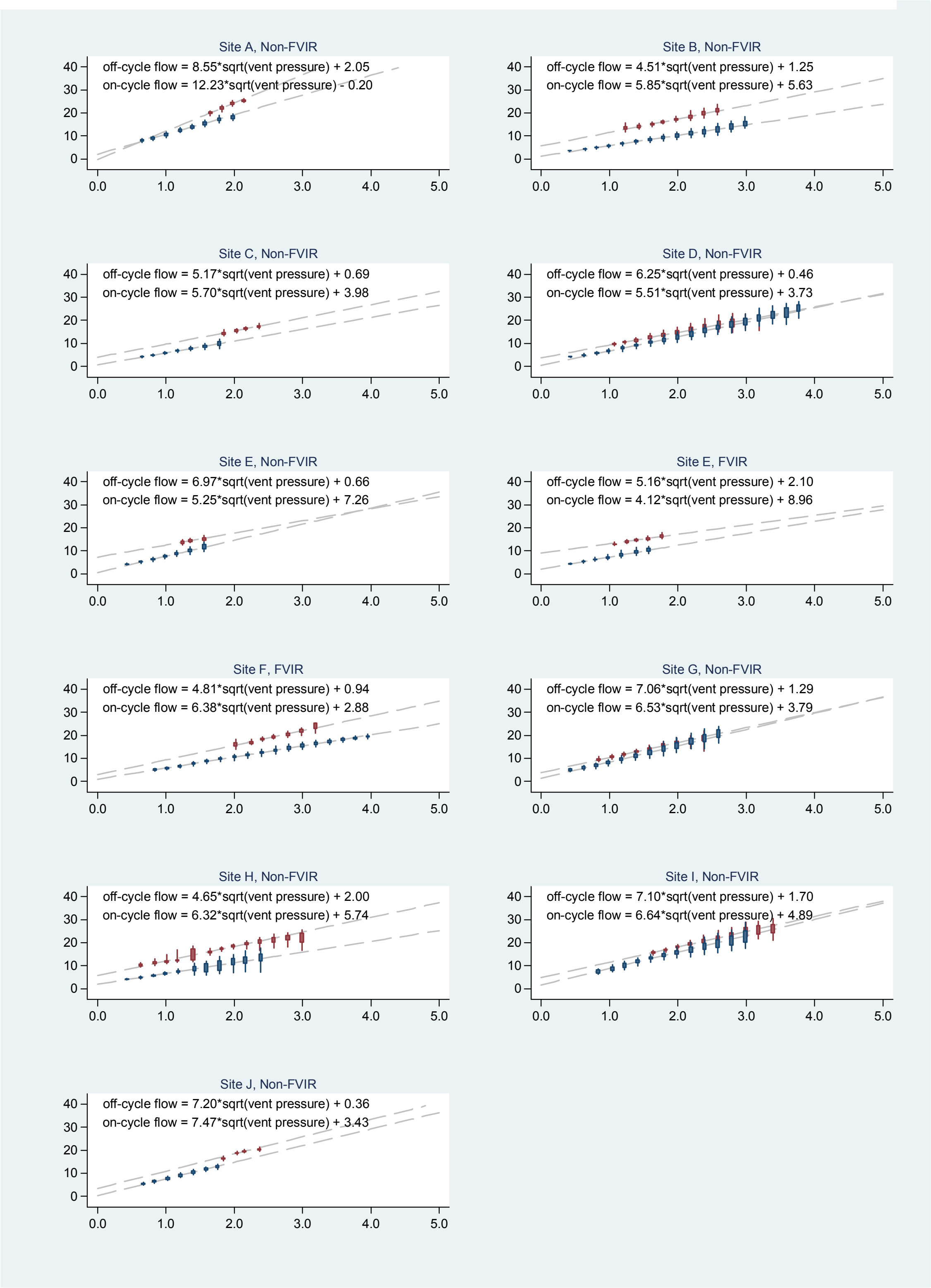
[29] We accounted for temperature-dependent differences in gas density by applying a correction factor to normalize the pressure data to 60F.

FIGURE 22. STOICHIOMETRICALLY-DERIVED FLOW VERSUS VENT PRESSURE, BY SITE



MODELING SEASONAL VENT FLOW

As might be expected, we found a strong relationship between daily vent flow and outdoor temperature: lower outdoor temperatures increase stack-effect forces in the vent system, which leads to increased flow through the venting system. Although in theory this flow should be proportional to the *square root* of the indoor-outdoor temperature difference, we found that the curvature is modest, and that a linear fit of vent flow to outdoor temperature is adequate.[30]

Obviously, the firing status of the water heater is also an important factor: we thus fit our analyzed daily vent flow as a function of outdoor temperature separately for periods when the water heater was firing versus not firing. The three sites where the water heater shared a venting system with a gas space heating system introduced an additional complication in that flow through the water heater's venting system is also affected by whether the *heating system* is firing. For these sites, we separately analyzed the four states defined by the combination of water heater and heating system main burner status (off/off, on/off, off/on and on/on).

TABLE 11. MODEL FITS FOR VENT FLOW VERSUS OUTDOOR TEMPERATURE, BY OPERATING MODEL

Model:

$$q = \beta_o + \beta_1 * T + \varepsilon$$

q = daily average water heater vent flow (cfm @ 60F)
T = daily average outdoor temperature
ε = random error

		Water heater not firing		Water heater firing	
Site		β_o	β_1	β_o	β_1
A		14.42	-0.074	11.10	0.014
B		8.61	-0.042	8.42	0.012
C		8.39	-0.050	7.54	0.024
D*	(heating system not firing)	14.09	-0.102	-0.03	0.057
	(heating system firing)	2.51	0.051	1.71	0.085
E		6.50	-0.040	7.80	0.017
F*	(heating system not firing)	10.11	-0.071	5.11	0.040
	(heating system firing)	15.52	-0.127	7.80	0.042
G		1.91	0.074	9.47	0.077
H*	(heating system not firing)	11.86	-0.080	2.78	0.032
	(heating system firing)	13.96	-0.108	7.09	0.046
I		-3.04	0.063	-1.14	0.083
J		16.27	-0.084	3.12	0.031

*Water heater venting shared with heating system

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[30] Wind also no doubt plays a role in vent system flow, but with an impact that is inherently difficult to model. The effect of wind on vent system flow is clearly evident in our data in moment-to-moment variation in vent pressure and calculated vent flow from moment to moment, but is treated here simply as scatter around the stack effect driving force, which dominates total flow through the system.

To translate these fitted relationships into estimates of monthly and seasonal average vent flow through each water heater, we used monthly temperature-bin data (for Madison, Wisconsin) to weight flow at each outdoor temperature by the incidence of each temperature bin.

To roll these estimates up to total flow accounting for both on- and off-cycle operation, it is necessary to know how much the water heater fires, which is a function of daily hot water use. The latter is highly variable from day to day at any given site, but we considered this day-to-day variation to be largely independent of outdoor temperature. However, to account for seasonal variation in hot water use that could be correlated with the weather (e.g., generally higher hot water consumption in the winter), we calculated average daily hot water use and water heater firing time separately for each month of the year. Thus, our estimates of monthly average water heater vent flow are a weighted combination of the distribution of outdoor temperatures and variation in hot water use over the year.

The sites that had shared venting with the heating system required some additional steps. Obviously, heating system firing time is highly correlated with outdoor temperature, so for these systems, not only is there increased stack effect from colder outdoor temperatures, but there is also additional heating-system operation that induces even more flow through the water heater side of the venting. While correlating heating system firing time with outdoor temperature is easy enough—and we could easily calculate monthly average water heater firing time—the challenge lay in modeling the amount of time that both devices would be firing at the same time.

Our approach was to specify yet another site-specific linear model, in this case a model of daily *joint* firing time as a function of both outdoor temperature and daily gallons of hot water used (Table 12). This provided the needed information to calculate the average amount of time in each of the four operating states as a function of outdoor temperature and hot water use. These could then be combined with estimates by operating state of vent flow as a function of outdoor temperature, and rolled up into monthly and seasonal estimates of average water vent flow.

TABLE 12. MODEL FITS FOR JOINT WATER HEATER / HEATING SYSTEM FIRING TIME (SITES WITH SHARED VENTING SYSTEM).

Model:

$$j = \beta_o + \beta_1 * T + \beta_2 * g + \varepsilon$$

j = daily hours of joint water heater / heating system firing
T = daily average outdoor temperature
g = daily gallons of hot water use
ε = random error

Site	β_o	β_1	β_2
D	0.259	-0.00927	0.00363
F	1.661	-0.03887	0.00409
H	0.465	-0.00730	0.00206

ESTIMATING HEATING LOAD

If the airflow through the water heater venting is known, it is relatively straightforward to calculate the convective heat flux involved from exhausting indoor air at a measured temperature and replacing it with outdoor air at a lower temperature. However, this heat flux does not necessarily (or even likely) represent the heating load imposed on the home's heating system, for two reasons.

First, a water heater vent system acts as a small thermally-driven exhaust fan in the basement. Other research has shown that—for reasons having to do with how a forced-exhaust device changes where air enters and leaves the house—typically only about half of the flow through a small exhaust device like this is incremental to natural infiltration (See "Combining Residential Infiltration and Mechanical Ventilation" in Chapter 27 in the ASHRAE Fundamentals [ASHRAE 2005]). In other words, if the water heater and its venting system were to be entirely removed from the house, the rate of natural infiltration in the home would decline by only about half the amount that formerly went through the venting system.

As a general rule of thumb, the ½-incremental-infiltration rule applies as long as the flow through the venting system is less than twice the natural infiltration rate. Even when firing in very cold weather, vent flows from our data were generally less than 25 cfm, and are almost always significantly less than the natural ventilation rate that one would expect in most houses (for example, a typical two-story home with moderate air leakage might have a natural infiltration rate of 60 cfm at 50F outdoor conditions and 160 cfm at 0F). For this reason, we counted only half the estimated vent flow through the water heater as contributing incrementally to the home's heating load.

Second, it is not a given that all of the heat required to raise the temperature of outdoor air to the temperature at which it enters the water heater is traceable to the home's heating system. Many water heaters are located in thermally semi-isolated basements, and some of the temperature rise in infiltration air may be provided by geothermal warming of air that enters through the building's foundation. To at least provide a range on this effect, we considered two extremes: (1) an assumption that all of the ΔT between outdoor and indoor water heater ambient temperature is made up by the home heating system; and (2) an assumption that the heating system only provides heat to make up the difference between the water heater ambient temperature and the average annual outdoor temperature, the latter as a proxy for long-term ground temperature.

APPENDIX D – DRAFT FORCES

The flow through the venting systems of natural-draft water heaters (and other natural-draft combustion appliances) is a function of a number of factors, including the relative temperatures (and densities) of combustion products in the vent system and of outdoor air, the vertical height of the venting system, frictional characteristics of the system, and the relative pressure of the room or combustion appliance zone compared to the outdoors.

In all cases, the functioning of a natural-draft chimney depends on the differential density of air in the chimney as compared to its environment. The environment in this case is outdoor air, since chimneys exhaust to outdoor air, and the temperature and density of outdoor air is the primary factor yielding a pressure difference at the base of a chimney (pressure differences across building envelopes will be addressed below). ASHRAE uses the term "theoretical draft" for this basic driving force in natural-draft chimney flow, and suggests it be calculated as follows[31]:

Theoretical draft (Pa) = 1902.1(H)(1/Tout – 1/Tvent)

where H is the vertical height of the vent system (ft), Tout is outdoor temperature (R), and Tvent is the mean vent temperature (R).

The full theoretical draft pressure is not necessarily available to drive vent flow, because any pressure drop across the building envelope (from outside to inside) reduces the net pressure difference.

Theoretical draft provides an upper limit on allowable depressurization; if zone depressurization exceeds theoretical draft, reverse flow in the chimney is inevitable. Figure 23 shows theoretical draft pressures for chimney heights typical of those we found in our research, at the lower range of temperatures characteristic of pilot-only operation. In general, the vent temperatures we observed were at least 30 degrees above outdoor ambient temperature, with the exception of the natural-draft water heater at Site F, where lower vent temperatures were in part a consequence of a very tall chimney.

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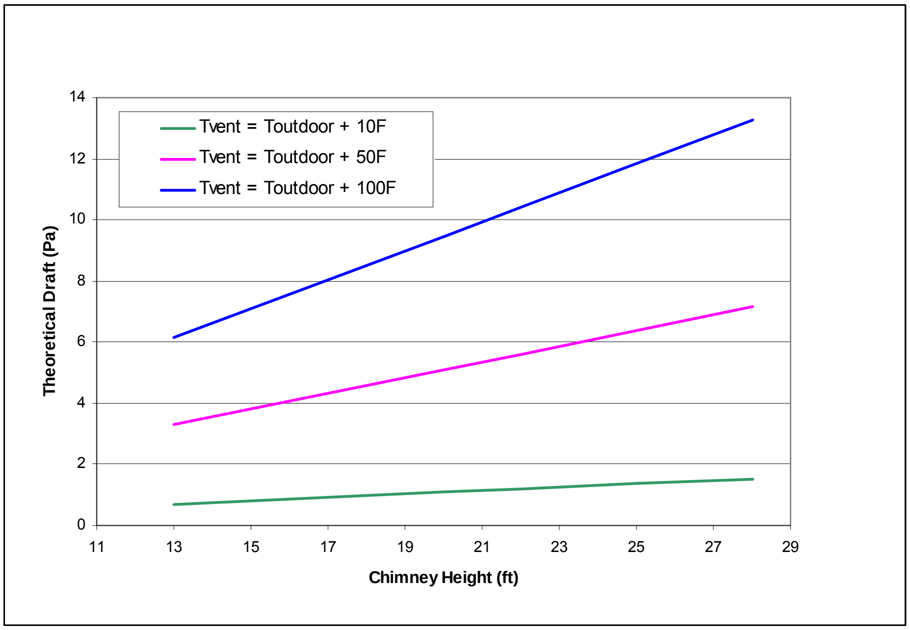
[31] HVAC Systems and Equipment Handbook, ASHRAE 2004, chapter 30. We have modified the equation as presented to use a standard pressure of 14.696 psia and to present the result in Pa.

FIGURE 23. THEORETICAL CHIMNEY DRAFT FOR VARYING VENT TEMPERATURE RISE (LOW RANGE) AT TOUT = 60F



These modest driving forces help explain downdrafting (flow reversal) in vent system during pilot-only operation. Flow reversal is more likely to occur when outdoor temperatures are moderately cool rather than very cold or hot, for two reasons. First, theoretical draft provides a lower driving force at moderate outdoor temperatures than at very cold temperatures, and thus is more easily overcome by wind or depressurization. Second, the depressurization of the basement (or location of chimney inlet) due to stack effect pressures when it is colder outside than inside encourages downdrafting.

Since chimneys venting water heaters are normally heated to some degree by continuous vent losses and maintain a continuous upward stack effect flow, the downdrafting must be initially established by a force sufficient to overcome the stack effect, at least for a brief period. These forces may include exhaust depressurization to a point that overcomes normal stack effect forces, or wind gusts, or a combination of these. Once the chimney is filled with the cooler air, the downflow may be self sustaining with only moderate depressurization of the combustion appliance zone.

Measured “draft pressure,” i.e. the pressure difference between a point just beyond the draft hood in the vent system with respect to the room or zone containing the vent system inlet, can on one hand be thought of as a measure of flow into the vent system: higher driving forces yield higher flows, and these higher flows are evidenced by higher pressure drop from room to vent. We used draft pressure, calibrated against flow rates derived from gas measurements for each system, as a general means of measuring vent flows in this study. Draft pressure is also one measure of the forces driving vent flow, though it is always less than the total driving force acting over the length of the chimney.

APPENDIX E – WATER HEATER EFFICIENCY AND SYSTEM EFFICIENCY

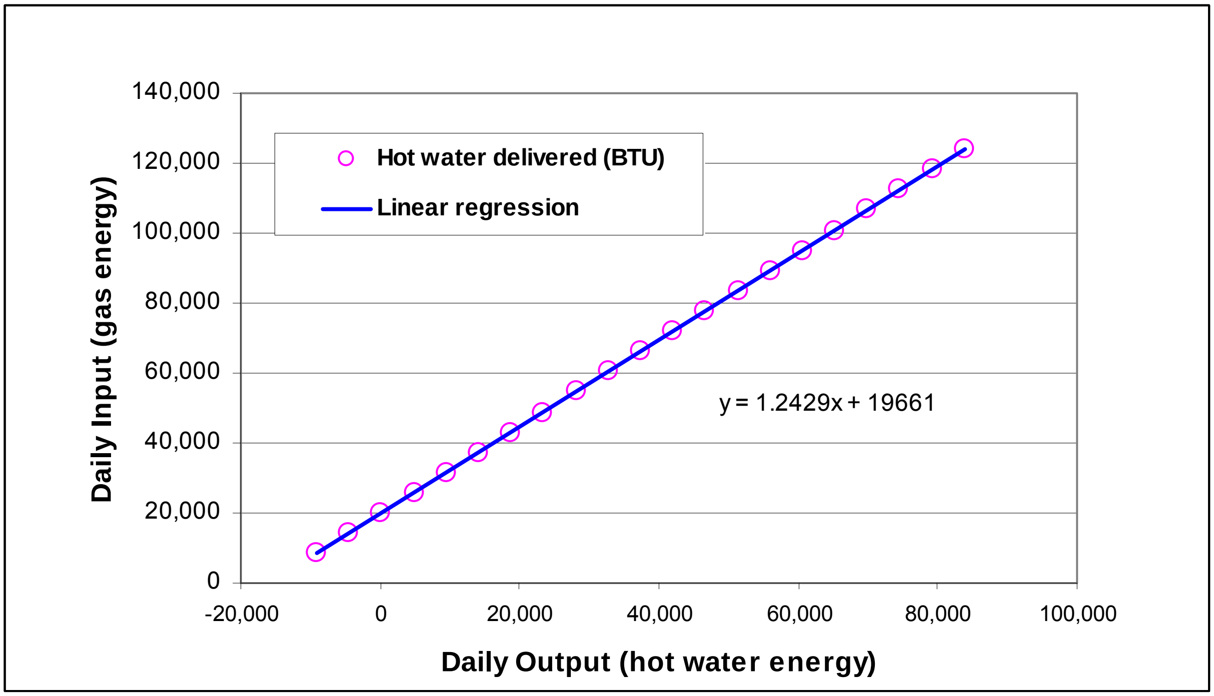
A general definition of efficiency for a heating appliance is the ratio of useful energy output to fuel energy input. Such a definition may be applied to the rate of conversion (i.e. on an instantaneous basis), or to accumulated values of energy input and output over time (e.g. a daily or seasonal basis). In the case of water heaters or other appliances with significant energy storage, these two interpretations are not interchangeable.

We use the term combustion efficiency, or instantaneous combustion efficiency, to mean the fraction of fuel energy that is captured by heating water. This is not the same as useful output, since a significant fraction of the heat captured in the water is generally lost through the water heater jacket. Combustion efficiency, nonetheless, is a useful metric for exploration of the heat transfer capability of a given water heater design. Combustion efficiencies of lower than around 70% imply poor heat transfer from combustion products to water, and may indicate the possibility of design improvements to the burner compartment and flue. We used instantaneous combustion efficiency to gauge the effect of mineral buildup in storage water heaters. Combustion efficiency during off cycle (pilot only) operation turned out to be particularly interesting; these efficiencies are typically quite low (or even negative), suggesting that standing pilot lights are a poor use of gas energy.

We use the term input-output efficiency to mean the total useful energy out divided by total fuel energy into a water heater, over some time period. We calculated the input-output efficiency on a daily basis, which is a long enough period so that minor differences in stored energy from the end of one day to the next do not have a major effect on calculated efficiency, but is short enough to allow exploration of the relationship between input and output through regressions.

When daily total output is plotted against daily total input for a storage tank water heater, the result generally is fairly linear, with an intercept that is a positive value of energy input. This regression provides a useful view of actual performance, in which the intercept is an estimate of the input required at no load (i.e. gas input required to make up tank standby losses), and the slope is the effective marginal efficiency with which the unit meets any additional load. It can be used to estimate the performance of a water heater under any range of loads (assuming water temperatures and room temperatures remain fixed). This regression, using synthetic values rather than real data, is shown in Figure 24. Note that with output on the x axis, and input on the y axis, the slope of the line is the reciprocal of the marginal efficiency, while the y-axis intercept is the correct estimate of input at zero load.

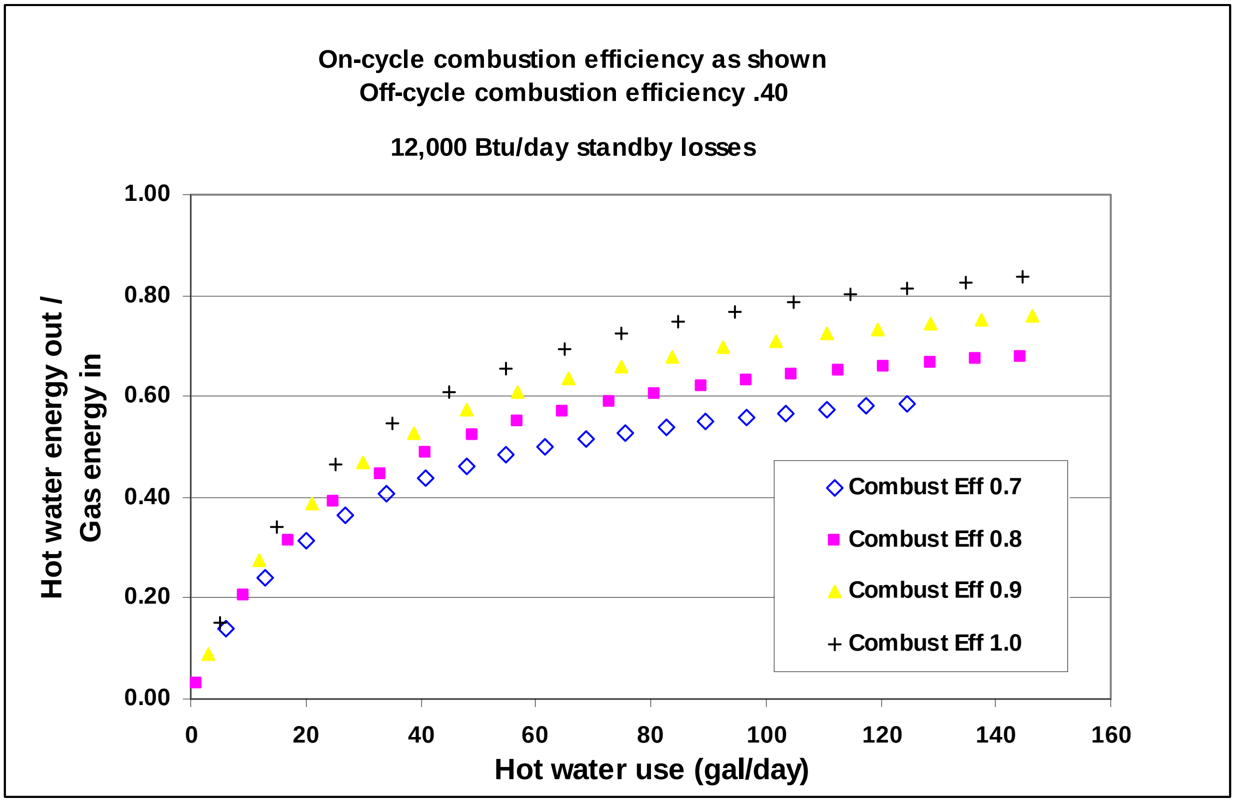
FIGURE 24. INPUT - OUTPUT RELATIONSHIP; THERMAL EFF: .80 ON CYCLE, .35 OFF CYCLE; STANDBY LOSS 12,000 BTU/DAY



In general, however, this effective marginal efficiency is not quite the same as the combustion efficiency of the main burner. If, as we found to be typical, the thermal efficiency for off cycle (pilot only) is lower than that during on cycle operation, the slope of the input output line reflects the fact that, as load increases, the higher on cycle combustion efficiency makes up a larger fraction of total input. This has the counterintuitive effect of increasing the slope of the input-output regression to a value greater than the on-cycle combustion efficiency.

Figure 25 shows typical trends of average input-output efficiency as water heater load increases.

FIGURE 25. THEORTICAL INPUT-OUTPUT EFFICIENCY



Water heating system efficiency

Our definitions and measurements of water heater efficiency are consistent with conventional views of appliance efficiency; they treat the appliance as a stand-alone device that converts fuel energy to a quantifiable useful output. In engineering terms, we place a control volume around the water heater, and measure inputs (gas and electricity) and outputs (hot water flow from the water heater) across that boundary. Any impact on the world outside the boundary is ignored. Appliances in real buildings, however, interact with space heating and cooling systems (and perhaps other systems) in several ways not considered in this simple efficiency model.

One of these, explored in this study, is the exhausting of conditioned air from the building via the water heater venting system. The conventional efficiency model implicitly assumes that air involved in combustion and venting is "energy neutral," equivalent to saying that makeup air never needs to be heated or cooled. Other ways in which conventionally defined efficiency fails to represent the overall performance of water heating systems in buildings include:

- Heat loss to the building from storage tank water heaters and to a lesser degree from tankless units, with an impact on heating and cooling loads.

- Heat loss from venting systems, especially when placed inside thermal envelopes, with an impact on heating and cooling loads.

- The delivery of hot water energy from the system that is not delivered to a useful load, but is left “stranded” in piping. When hot water energy is measured near the water heater, all flows are assumed to contribute to useful energy delivery, but stranded flows energy should not be counted.

- Heat loss from hot water piping during and after hot water draws, with an impact on heating and cooling loads.

- Heat loss and evaporation during hot water use, with an impact on heating, cooling, and dehumidification loads.

APPENDIX F – ESTIMATED OPERATING COSTS AND EFFICIENCIES

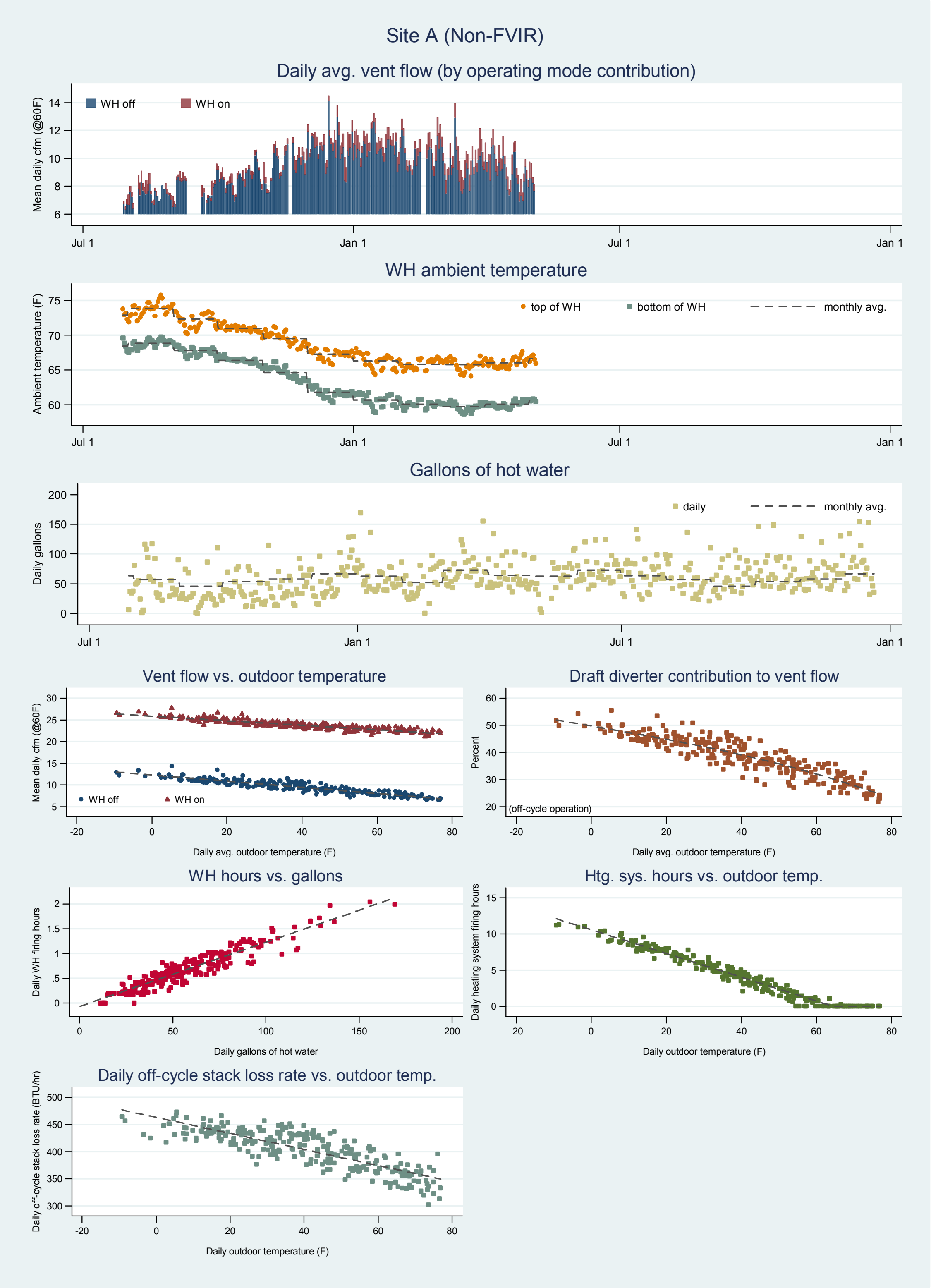
TABLE 13. ESTIMATED OPERATING COSTS AND OVERALL INPUT/OUTPUT EFFICIENCIES OF TESTED WATER HEATERS NORMALIZED TO 60F TEMPERATURE RISE

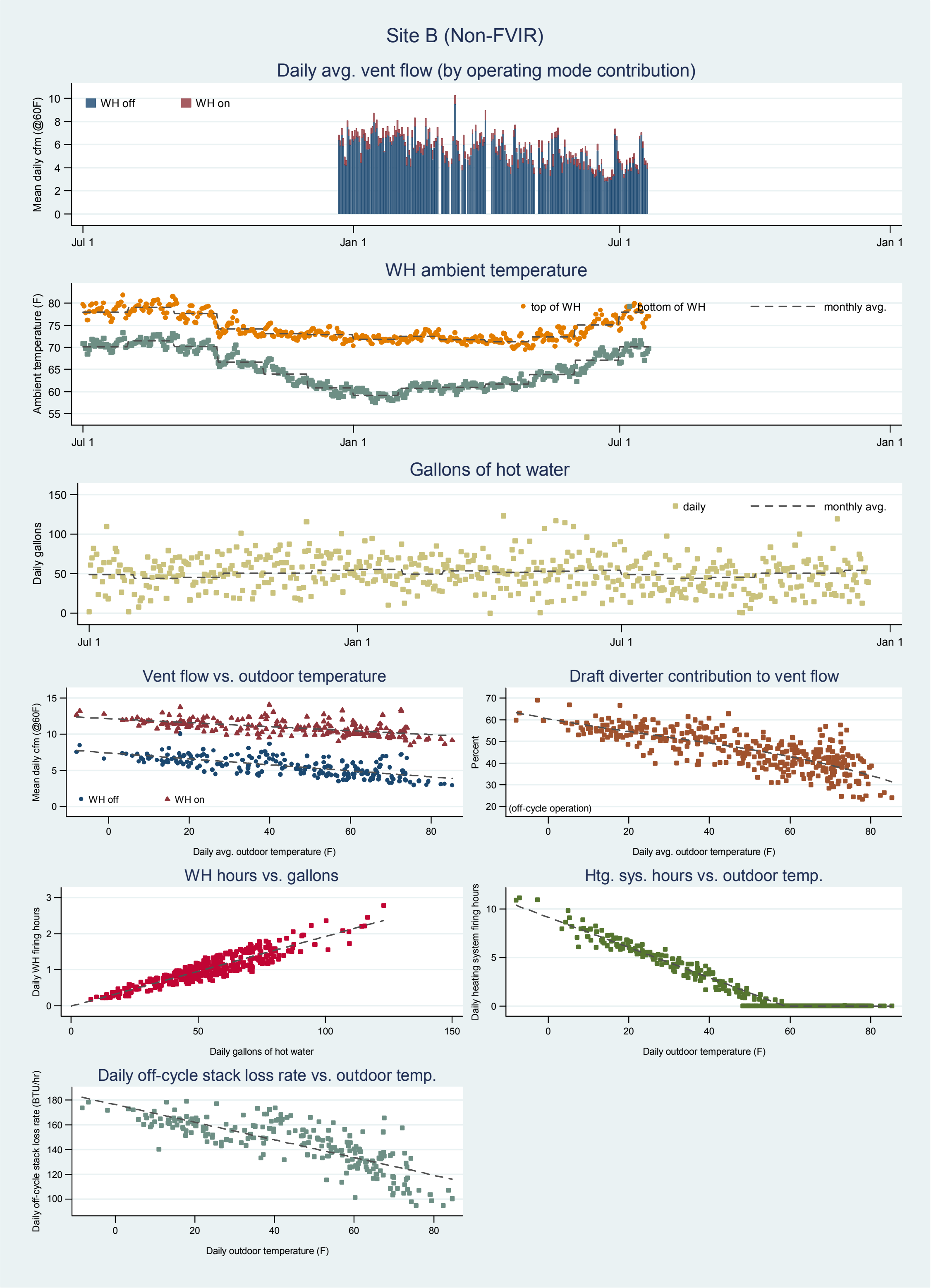
Site	Type	Hot water gal/day	therms/yr	$/yr	kWh/yr	$/yr	$/yr	Overall i/o efficiency
A	Natural-draft	0	146.7	$146.68	0.0	$0.00	$146.68	36.7%
A	Natural-draft	25	171.2	$171.23	0.0	$0.00	$171.23	31.1%
A	Natural-draft	50	248.0	$248.02	0.0	$0.00	$248.02	42.9%
A	Natural-draft	75	324.8	$324.82	0.0	$0.00	$324.82	49.1%
A	Natural-draft	100	401.6	$401.62	0.0	$0.00	$401.62	53.0%
A	Tankless	0	80.4	$80.44	20.1	$2.41	$82.86	76.2%
A	Tankless	25	71.8	$71.81	19.7	$2.37	$74.18	74.1%
A	Tankless	50	138.9	$138.95	22.6	$2.71	$141.66	76.6%
A	Tankless	75	206.1	$206.09	25.4	$3.05	$209.14	77.5%
A	Tankless	100	273.2	$273.23	28.2	$3.39	$276.62	77.9%
B	Natural-draft	0	174.3	$174.32	0.0	$0.00	$174.32	56.6%
B	Natural-draft	25	112.5	$112.47	0.0	$0.00	$112.47	47.3%
B	Natural-draft	50	184.3	$184.30	0.0	$0.00	$184.30	57.7%
B	Natural-draft	75	256.1	$256.13	0.0	$0.00	$256.13	62.3%
B	Natural-draft	100	328.0	$327.96	0.0	$0.00	$327.96	64.9%
B	Condensing tankless	0	25.9	$25.90	54.9	$6.59	$32.48	89.2%
B	Condensing tankless	25	60.5	$60.50	58.2	$6.98	$67.48	87.9%
B	Condensing tankless	50	118.2	$118.19	63.7	$7.64	$125.83	90.0%
B	Condensing tankless	75	175.9	$175.88	69.2	$8.30	$184.19	90.8%
B	Condensing tankless	100	233.6	$233.57	74.7	$8.96	$242.54	91.1%
C	Natural-draft	0	163.2	$163.24	0.0	$0.00	$163.24	61.7%
C	Natural-draft	25	114.8	$114.78	0.0	$0.00	$114.78	46.4%
C	Natural-draft	50	181.9	$181.93	0.0	$0.00	$181.93	58.5%
C	Natural-draft	75	249.1	$249.08	0.0	$0.00	$249.08	64.1%
C	Natural-draft	100	316.2	$316.24	0.0	$0.00	$316.24	67.3%
C	Power-vent	0	107.9	$107.85	52.1	$6.25	$114.10	65.0%
C	Power-vent	25	102.5	$102.54	49.8	$5.98	$108.51	51.9%
C	Power-vent	50	168.1	$168.15	77.5	$9.30	$177.45	63.3%
C	Power-vent	75	233.8	$233.76	105.2	$12.62	$246.39	68.3%
C	Power-vent	100	299.4	$299.38	132.9	$15.95	$315.32	71.1%
D	Natural-draft	0	179.6	$179.55	0.0	$0.00	$179.55	60.9%
D	Natural-draft	25	113.6	$113.64	0.0	$0.00	$113.64	46.8%
D	Natural-draft	50	184.6	$184.63	0.0	$0.00	$184.63	57.6%
D	Natural-draft	75	255.6	$255.61	0.0	$0.00	$255.61	62.4%
D	Natural-draft	100	326.6	$326.60	0.0	$0.00	$326.60	65.2%
D	Power-vent	0	122.6	$122.62	59.7	$7.16	$129.78	71.1%

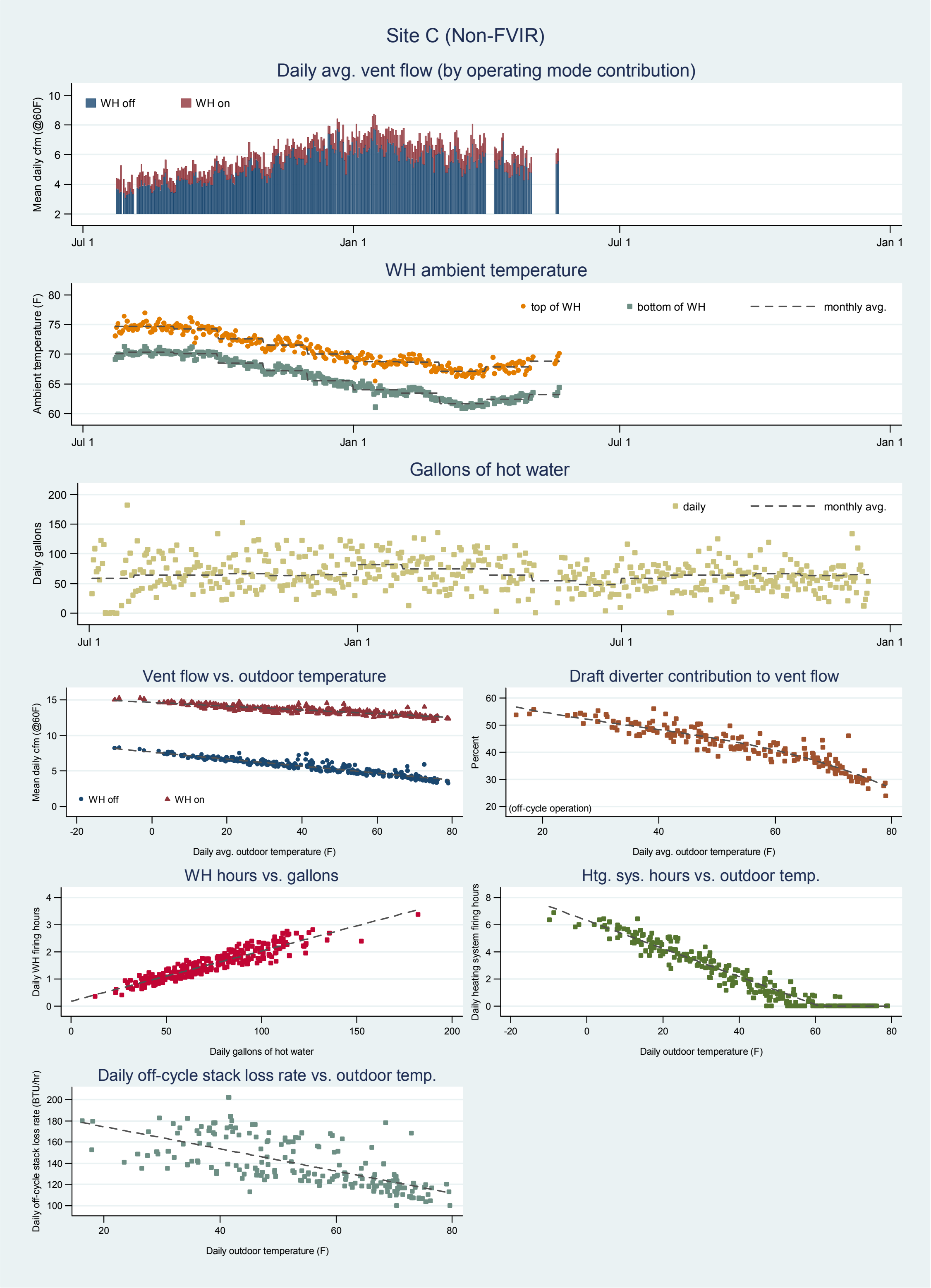
Site	Type	Hot water gal/day	therms/yr	$/yr	kWh/yr	$/yr	$/yr	Overall i/o efficiency
D	Power-vent	25	91.0	$90.97	45.9	$5.50	$96.48	58.5%
D	Power-vent	50	155.8	$155.76	74.1	$8.90	$164.65	68.3%
D	Power-vent	75	220.5	$220.54	102.4	$12.29	$232.83	72.4%
D	Power-vent	100	285.3	$285.32	130.7	$15.68	$301.00	74.6%
E	Natural-draft	0	145.7	$145.72	0.0	$0.00	$145.72	57.4%
E	Natural-draft	25	119.9	$119.90	0.0	$0.00	$119.90	44.4%
E	Natural-draft	50	192.2	$192.23	0.0	$0.00	$192.23	55.4%
E	Natural-draft	75	264.6	$264.57	0.0	$0.00	$264.57	60.3%
E	Natural-draft	100	336.9	$336.90	0.0	$0.00	$336.90	63.2%
E	Natural-draft FVIR	0	69.1	$69.05	0.0	$0.00	$69.05	60.4%
E	Natural-draft FVIR	25	134.5	$134.47	0.0	$0.00	$134.47	39.6%
E	Natural-draft FVIR	50	205.6	$205.62	0.0	$0.00	$205.62	51.8%
E	Natural-draft FVIR	75	276.8	$276.77	0.0	$0.00	$276.77	57.7%
E	Natural-draft FVIR	100	347.9	$347.93	0.0	$0.00	$347.93	61.2%
E	Tankless	0	75.3	$75.30	21.2	$2.54	$77.85	79.7%
E	Tankless	25	69.8	$69.77	20.9	$2.51	$72.28	76.3%
E	Tankless	50	134.1	$134.11	24.1	$2.89	$137.00	79.3%
E	Tankless	75	198.4	$198.45	27.2	$3.27	$201.71	80.4%
E	Tankless	100	262.8	$262.79	30.4	$3.64	$266.43	81.0%
F	Natural-draft FVIR	0	212.9	$212.92	0.0	$0.00	$212.92	62.6%
F	Natural-draft FVIR	25	160.8	$160.81	0.0	$0.00	$160.81	33.1%
F	Natural-draft FVIR	50	229.7	$229.74	0.0	$0.00	$229.74	46.3%
F	Natural-draft FVIR	75	298.7	$298.67	0.0	$0.00	$298.67	53.4%
F	Natural-draft FVIR	100	367.6	$367.59	0.0	$0.00	$367.59	57.9%
F	Condensing power-vent	0	25.0	$25.01	24.2	$2.90	$27.91	82.8%
F	Condensing power-vent	25	94.8	$94.85	35.8	$4.29	$99.14	56.1%
F	Condensing power-vent	50	153.8	$153.80	45.6	$5.47	$159.27	69.2%
F	Condensing power-vent	75	212.8	$212.76	55.3	$6.64	$219.40	75.0%
F	Condensing power-vent	100	271.7	$271.72	65.1	$7.81	$279.53	78.3%
G	Natural-draft	0	81.1	$81.13	0.0	$0.00	$81.13	55.2%
G	Natural-draft	25	126.0	$125.96	0.0	$0.00	$125.96	42.2%
G	Natural-draft	50	196.6	$196.61	0.0	$0.00	$196.61	54.1%
G	Natural-draft	75	267.3	$267.25	0.0	$0.00	$267.25	59.7%
G	Natural-draft	100	337.9	$337.90	0.0	$0.00	$337.90	63.0%
G	Power-vent	0	54.0	$54.03	30.0	$3.60	$57.64	56.2%
G	Power-vent	25	95.1	$95.09	48.8	$5.86	$100.95	56.0%

Site	Type	Hot water gal/day	therms/yr	$/yr	kWh/yr	$/yr	$/yr	Overall i/o efficiency
G	Power-vent	50	161.8	$161.77	79.4	$9.53	$171.30	65.8%
G	Power-vent	75	228.5	$228.45	109.9	$13.19	$241.65	69.9%
G	Power-vent	100	295.1	$295.14	140.5	$16.86	$311.99	72.1%
H	Natural-draft	0	49.3	$49.30	0.0	$0.00	$49.30	56.7%
H	Natural-draft	25	120.1	$120.13	0.0	$0.00	$120.13	44.3%
H	Natural-draft	50	195.6	$195.55	0.0	$0.00	$195.55	54.4%
H	Natural-draft	75	271.0	$270.97	0.0	$0.00	$270.97	58.9%
H	Natural-draft	100	346.4	$346.39	0.0	$0.00	$346.39	61.4%
H	Tankless	0	35.7	$35.74	24.3	$2.92	$38.66	74.5%
H	Tankless	25	71.7	$71.69	26.0	$3.12	$74.81	74.2%
H	Tankless	50	139.2	$139.19	29.1	$3.49	$142.69	76.5%
H	Tankless	75	206.7	$206.70	32.3	$3.87	$210.57	77.2%
H	Tankless	100	274.2	$274.20	35.4	$4.25	$278.45	77.6%
I	Natural-draft	0	114.3	$114.32	0.0	$0.00	$114.32	67.1%
I	Natural-draft	25	141.9	$141.89	0.0	$0.00	$141.89	37.5%
I	Natural-draft	50	195.3	$195.33	0.0	$0.00	$195.33	54.5%
I	Natural-draft	75	248.8	$248.77	0.0	$0.00	$248.77	64.2%
I	Natural-draft	100	302.2	$302.21	0.0	$0.00	$302.21	70.4%
I	Tankless	0	107.3	$107.28	23.3	$2.79	$110.07	75.0%
I	Tankless	25	76.1	$76.14	21.9	$2.63	$78.77	69.9%
I	Tankless	50	143.7	$143.71	24.8	$2.98	$146.69	74.1%
I	Tankless	75	211.3	$211.27	27.8	$3.33	$214.60	75.6%
I	Tankless	100	278.8	$278.83	30.7	$3.68	$282.51	76.3%
J	Natural-draft	0	111.4	$111.38	0.0	$0.00	$111.38	40.5%
J	Natural-draft	25	184.3	$184.33	0.0	$0.00	$184.33	28.9%
J	Natural-draft	50	266.4	$266.43	0.0	$0.00	$266.43	39.9%
J	Natural-draft	75	348.5	$348.54	0.0	$0.00	$348.54	45.8%
J	Natural-draft	100	430.6	$430.64	0.0	$0.00	$430.64	49.4%
J	Power-vent	0	27.3	$27.27	18.3	$2.19	$29.47	56.4%
J	Power-vent	25	115.7	$115.67	54.5	$6.54	$122.21	46.0%
J	Power-vent	50	184.2	$184.22	82.6	$9.91	$194.13	57.8%
J	Power-vent	75	252.8	$252.78	110.7	$13.28	$266.06	63.1%
J	Power-vent	100	321.3	$321.33	138.8	$16.66	$337.99	66.2%

APPENDIX G – MEASURED PERFORMANCE CHARACTERISTICS OF WATER HEATERS




Site B (Non-FVIR)
Daily avg. vent flow (by operating mode contribution)
Mean daily cfm (@60F)
WH off
WH on
0
2
4
6
8
10
Jul 1
Jan 1
Jul 1
Jan 1
WH ambient temperature
Ambient temperature (F)
top of WH
bottom of WH
monthly avg.
55
60
65
70
75
80
Jul 1
Jan 1
Jul 1
Jan 1
Gallons of hot water
Daily gallons
daily
monthly avg.
0
50
100
150
Jul 1
Jan 1
Jul 1
Jan 1
Vent flow vs. outdoor temperature
Mean daily cfm (@60F)
WH off
WH on
0
5
10
15
0
20
40
60
80
Daily avg. outdoor temperature (F)
Draft diverter contribution to vent flow
Percent
(off-cycle operation)
20
30
40
50
60
70
0
20
40
60
80
Daily avg. outdoor temperature (F)
WH hours vs. gallons
Daily WH firing hours
0
1
2
3
0
50
100
150
Daily gallons of hot water
Htg. sys. hours vs. outdoor temp.
Daily heating system firing hours
0
5
10
0
20
40
60
80
Daily outdoor temperature (F)
Daily off-cycle stack loss rate vs. outdoor temp.
Daily off-cycle stack loss rate (BTU/hr)
100
120
140
160
180
0
20
40
60
80
Daily outdoor temperature (F)


Site C (Non-FVIR)

Daily avg. vent flow (by operating mode contribution)

WH ambient temperature

Gallons of hot water

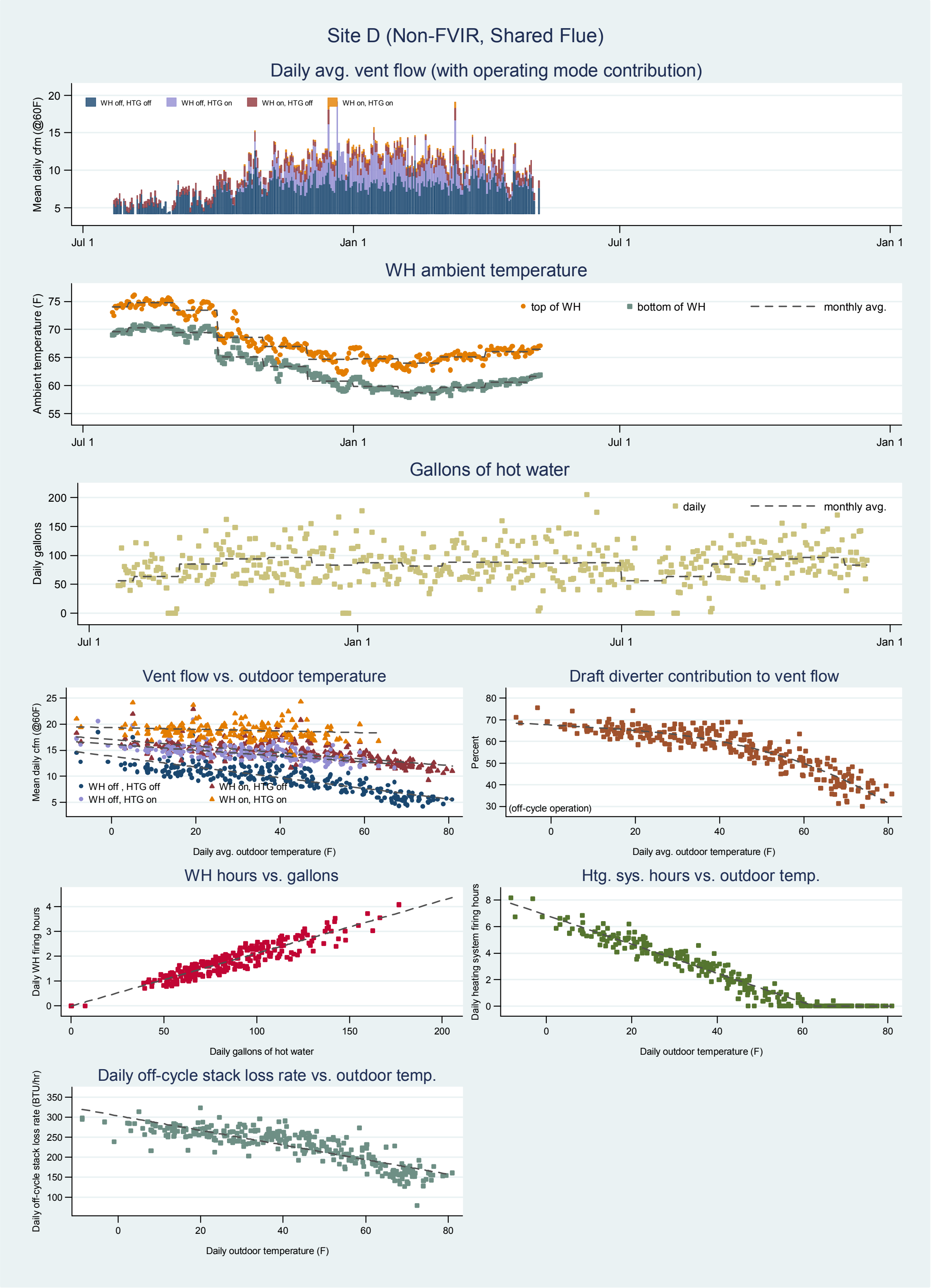
Vent flow vs. outdoor temperature

Draft diverter contribution to vent flow

WH hours vs. gallons

Htg. sys. hours vs. outdoor temp.

Daily off-cycle stack loss rate vs. outdoor temp.



Site D (Non-FVIR, Shared Flue)

Daily avg. vent flow (with operating mode contribution)

WH ambient temperature

Gallons of hot water

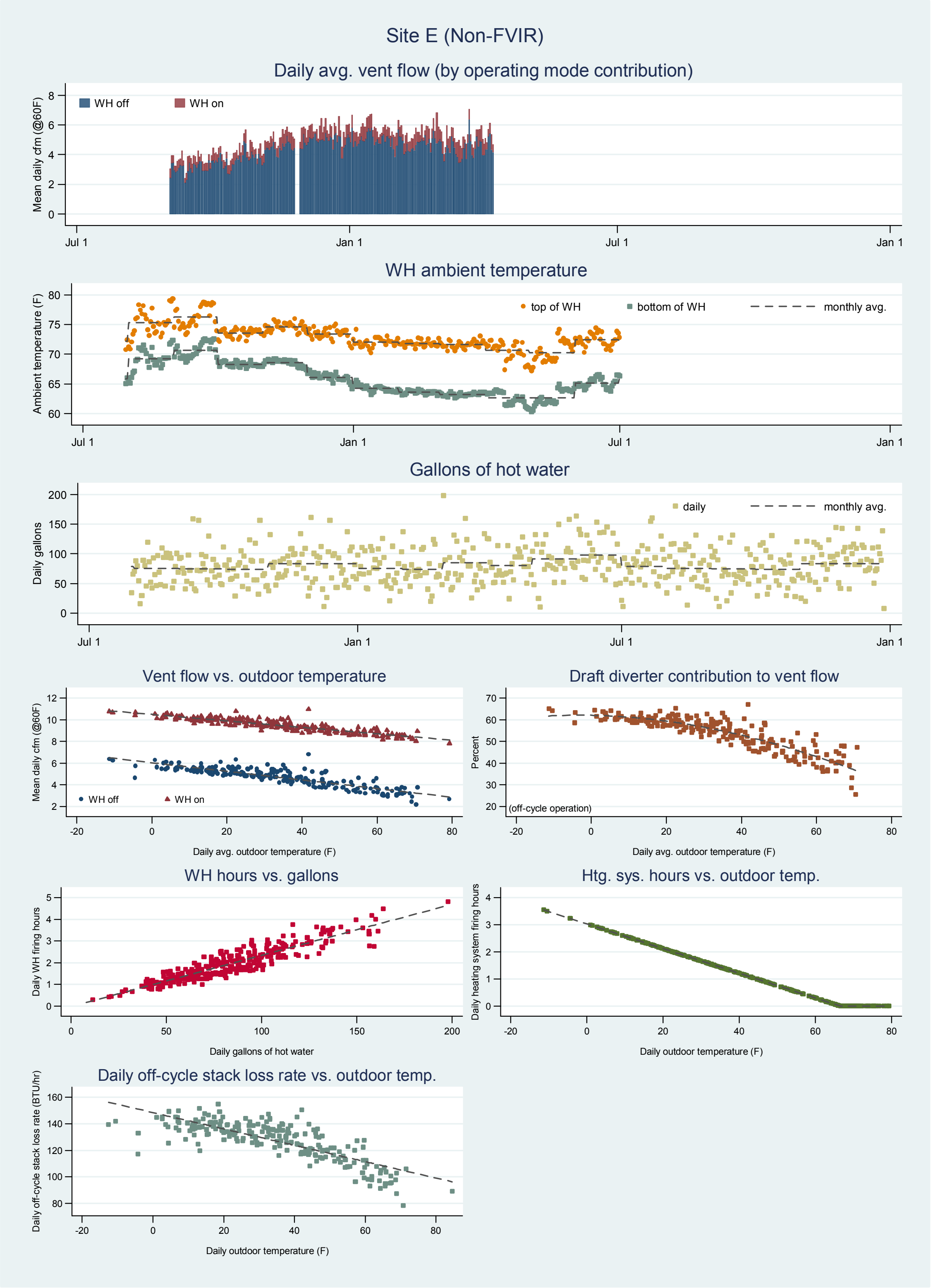
Vent flow vs. outdoor temperature

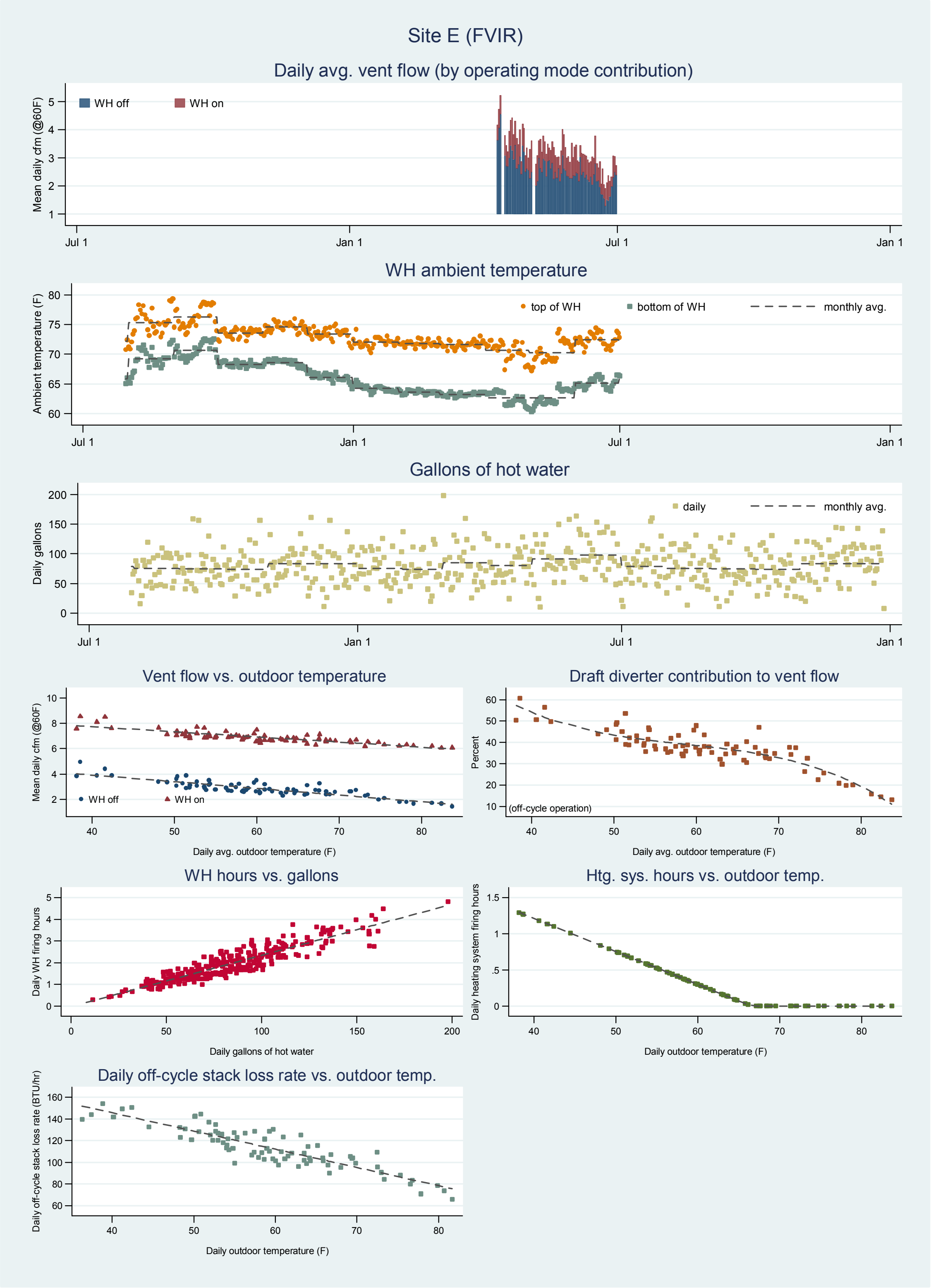
Draft diverter contribution to vent flow

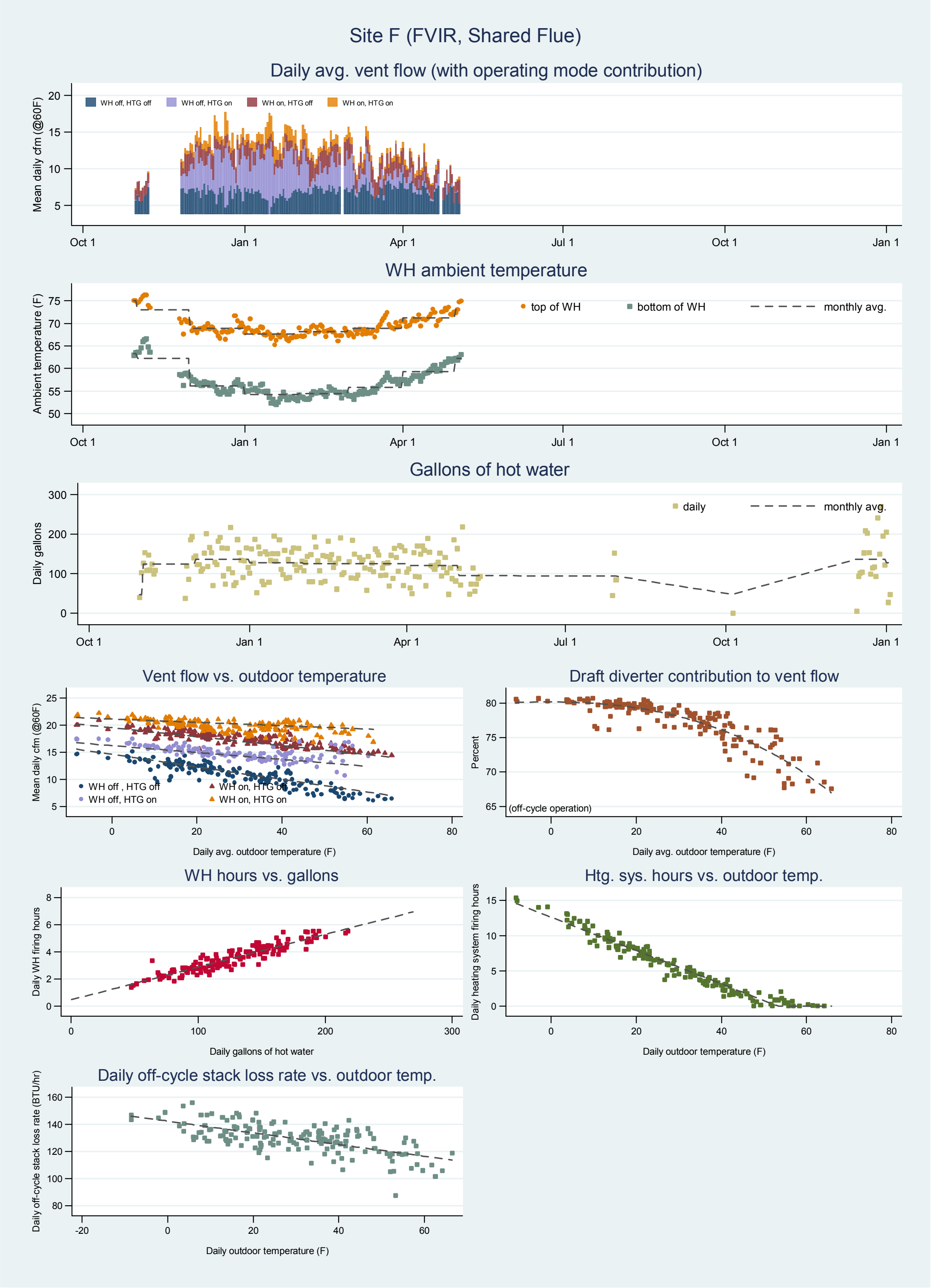
WH hours vs. gallons

Htg. sys. hours vs. outdoor temp.

Daily off-cycle stack loss rate vs. outdoor temp.


Site E (Non-FVIR)
Daily avg. vent flow (by operating mode contribution)
Mean daily cfm (@60F)
0
2
4
6
8
WH off
WH on
Jul 1
Jan 1
Jul 1
Jan 1
WH ambient temperature
Ambient temperature (F)
60
65
70
75
80
top of WH
bottom of WH
monthly avg.
Jul 1
Jan 1
Jul 1
Jan 1
Gallons of hot water
Daily gallons
0
50
100
150
200
daily
monthly avg.
Jul 1
Jan 1
Jul 1
Jan 1
Vent flow vs. outdoor temperature
Mean daily cfm (@60F)
2
4
6
8
10
12
WH off
WH on
-20
0
20
40
60
80
Daily avg. outdoor temperature (F)
Draft diverter contribution to vent flow
Percent
20
30
40
50
60
70
(off-cycle operation)
-20
0
20
40
60
80
Daily avg. outdoor temperature (F)
WH hours vs. gallons
Daily WH firing hours
0
1
2
3
4
5
0
50
100
150
200
Daily gallons of hot water
Htg. sys. hours vs. outdoor temp.
Daily heating system firing hours
0
1
2
3
4
-20
0
20
40
60
80
Daily outdoor temperature (F)
Daily off-cycle stack loss rate vs. outdoor temp.
Daily off-cycle stack loss rate (BTU/hr)
80
100
120
140
160
-20
0
20
40
60
80
Daily outdoor temperature (F)


Site E (FVIR)
Daily avg. vent flow (by operating mode contribution)
Mean daily cfm (@60F)
1
2
3
4
5
WH off
WH on
Jul 1
Jan 1
Jul 1
Jan 1
WH ambient temperature
Ambient temperature (F)
60
65
70
75
80
top of WH
bottom of WH
monthly avg.
Jul 1
Jan 1
Jul 1
Jan 1
Gallons of hot water
Daily gallons
0
50
100
150
200
daily
monthly avg.
Jul 1
Jan 1
Jul 1
Jan 1
Vent flow vs. outdoor temperature
Mean daily cfm (@60F)
2
4
6
8
10
WH off
WH on
40
50
60
70
80
Daily avg. outdoor temperature (F)
Draft diverter contribution to vent flow
Percent
10
20
30
40
50
60
(off-cycle operation)
40
50
60
70
80
Daily avg. outdoor temperature (F)
WH hours vs. gallons
Daily WH firing hours
0
1
2
3
4
5
0
50
100
150
200
Daily gallons of hot water
Htg. sys. hours vs. outdoor temp.
Daily heating system firing hours
0
.5
1
1.5
40
50
60
70
80
Daily outdoor temperature (F)
Daily off-cycle stack loss rate vs. outdoor temp.
Daily off-cycle stack loss rate (BTU/hr)
60
80
100
120
140
160
40
50
60
70
80
Daily outdoor temperature (F)



Site F (FVIR, Shared Flue)

Daily avg. vent flow (with operating mode contribution)

WH ambient temperature

Gallons of hot water

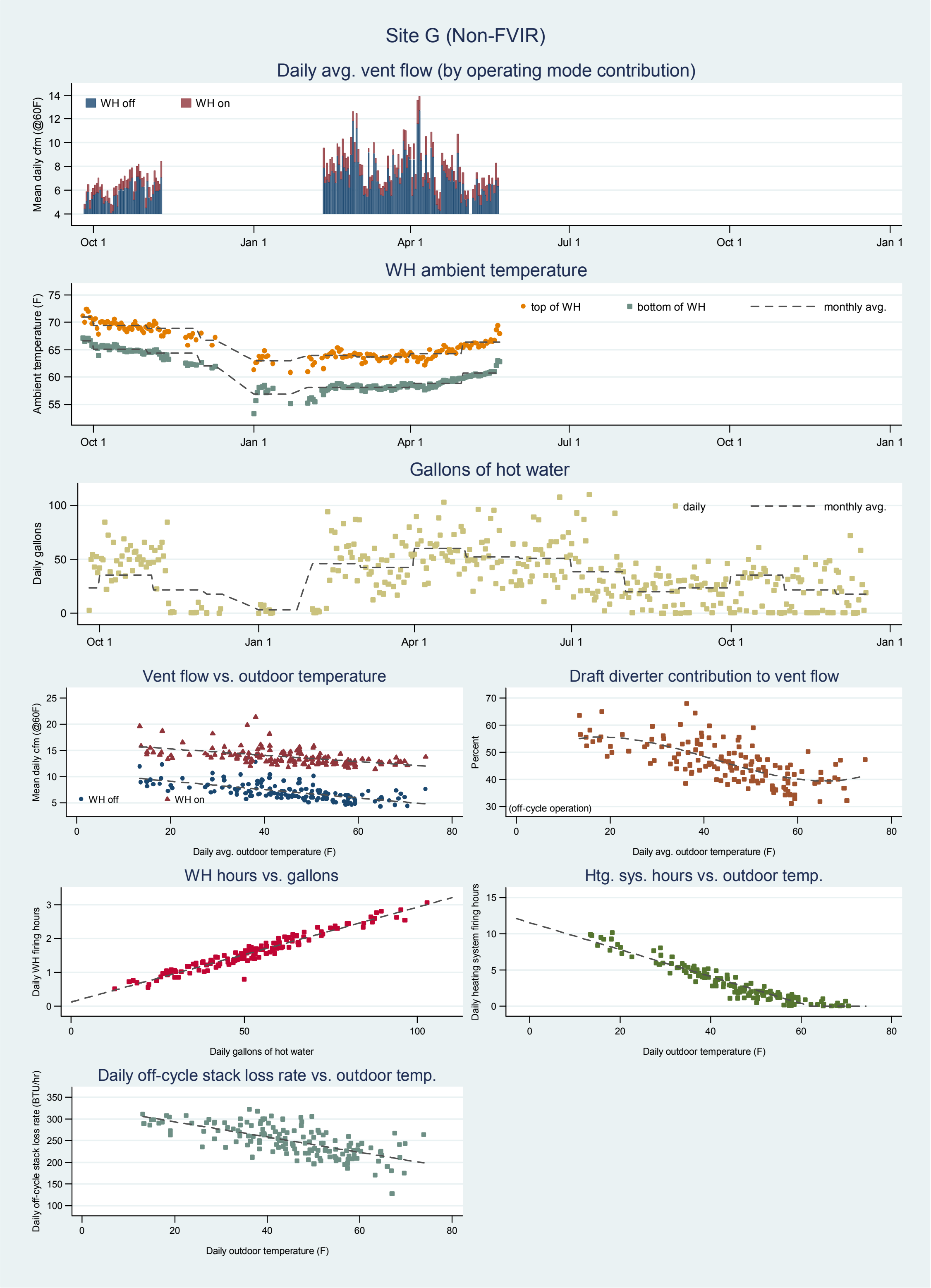
Vent flow vs. outdoor temperature

Draft diverter contribution to vent flow

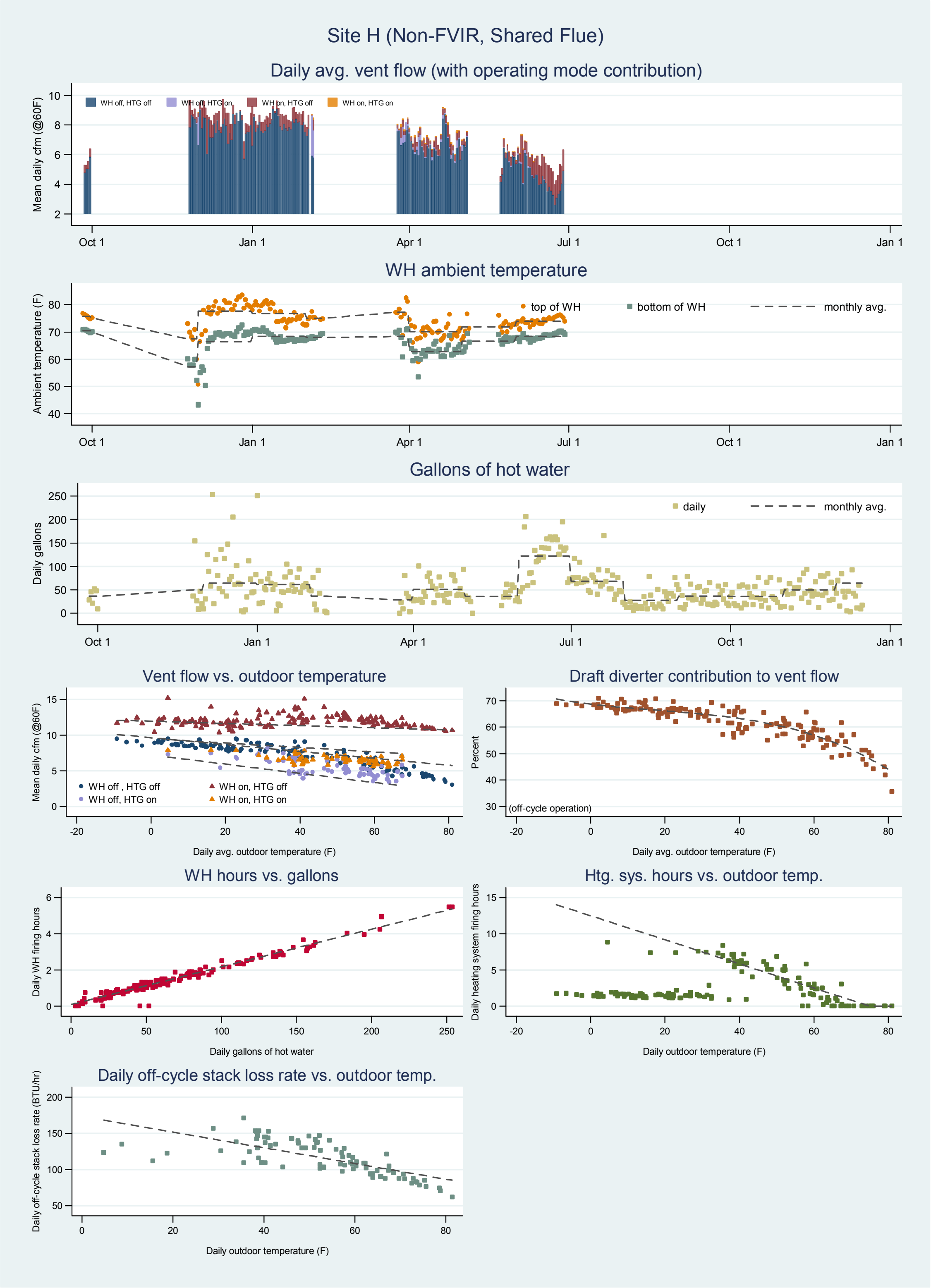
WH hours vs. gallons

Htg. sys. hours vs. outdoor temp.

Daily off-cycle stack loss rate vs. outdoor temp.



Site G (Non-FVIR)
Daily avg. vent flow (by operating mode contribution)
Mean daily cfm (@60F)
WH off
WH on
4
6
8
10
12
14
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
WH ambient temperature
Ambient temperature (F)
top of WH
bottom of WH
monthly avg.
55
60
65
70
75
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
Gallons of hot water
Daily gallons
daily
monthly avg.
0
50
100
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
Vent flow vs. outdoor temperature
Mean daily cfm (@60F)
WH off
WH on
5
10
15
20
25
0
20
40
60
80
Daily avg. outdoor temperature (F)
Draft diverter contribution to vent flow
Percent
(off-cycle operation)
30
40
50
60
70
0
20
40
60
80
Daily avg. outdoor temperature (F)
WH hours vs. gallons
Daily WH firing hours
0
1
2
3
0
50
100
Daily gallons of hot water
Htg. sys. hours vs. outdoor temp.
Daily heating system firing hours
0
5
10
15
0
20
40
60
80
Daily outdoor temperature (F)
Daily off-cycle stack loss rate vs. outdoor temp.
Daily off-cycle stack loss rate (BTU/hr)
100
150
200
250
300
350
0
20
40
60
80
Daily outdoor temperature (F)



Site H (Non-FVIR, Shared Flue)

Daily avg. vent flow (with operating mode contribution)

WH ambient temperature

Gallons of hot water

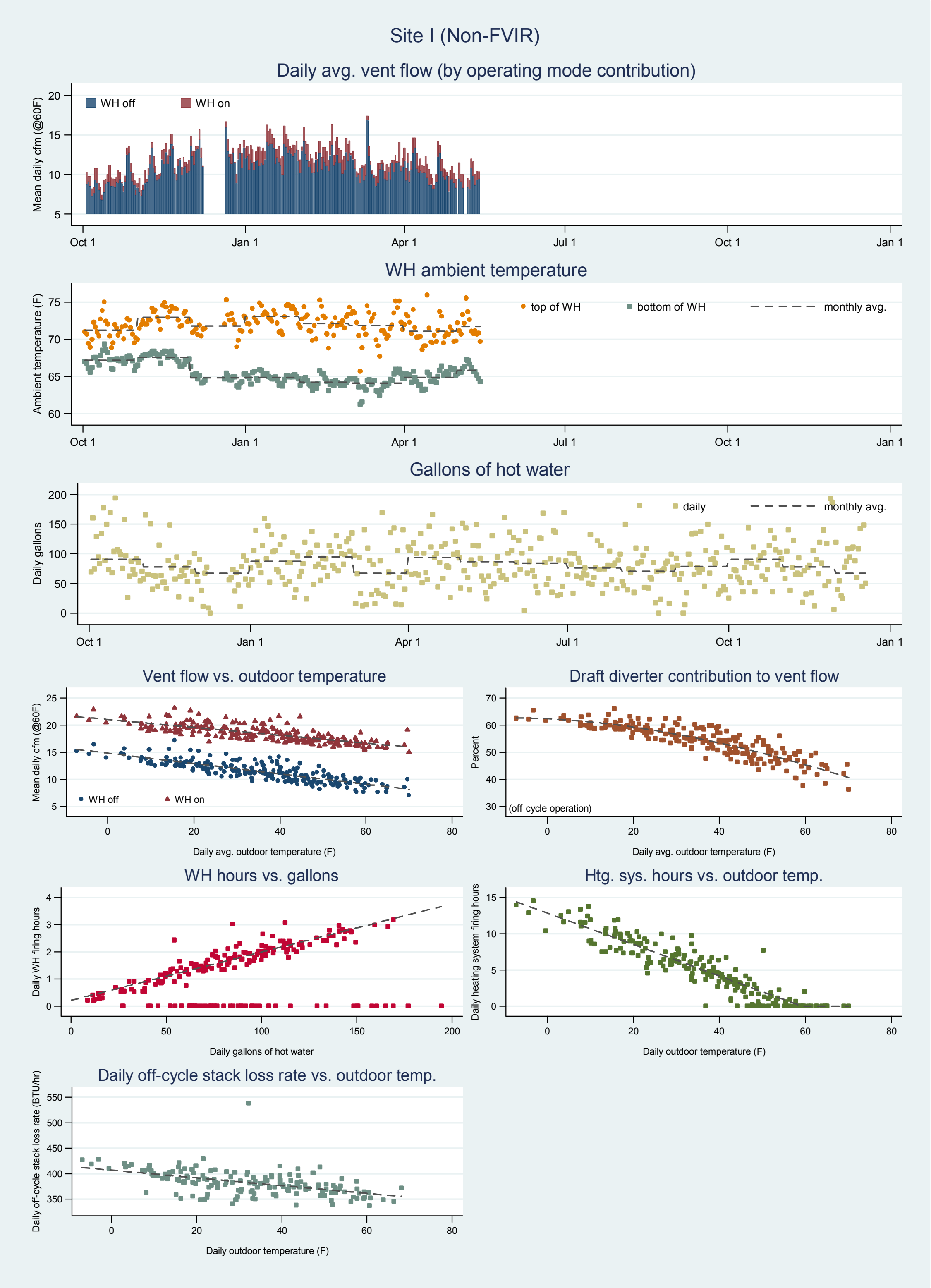
Vent flow vs. outdoor temperature

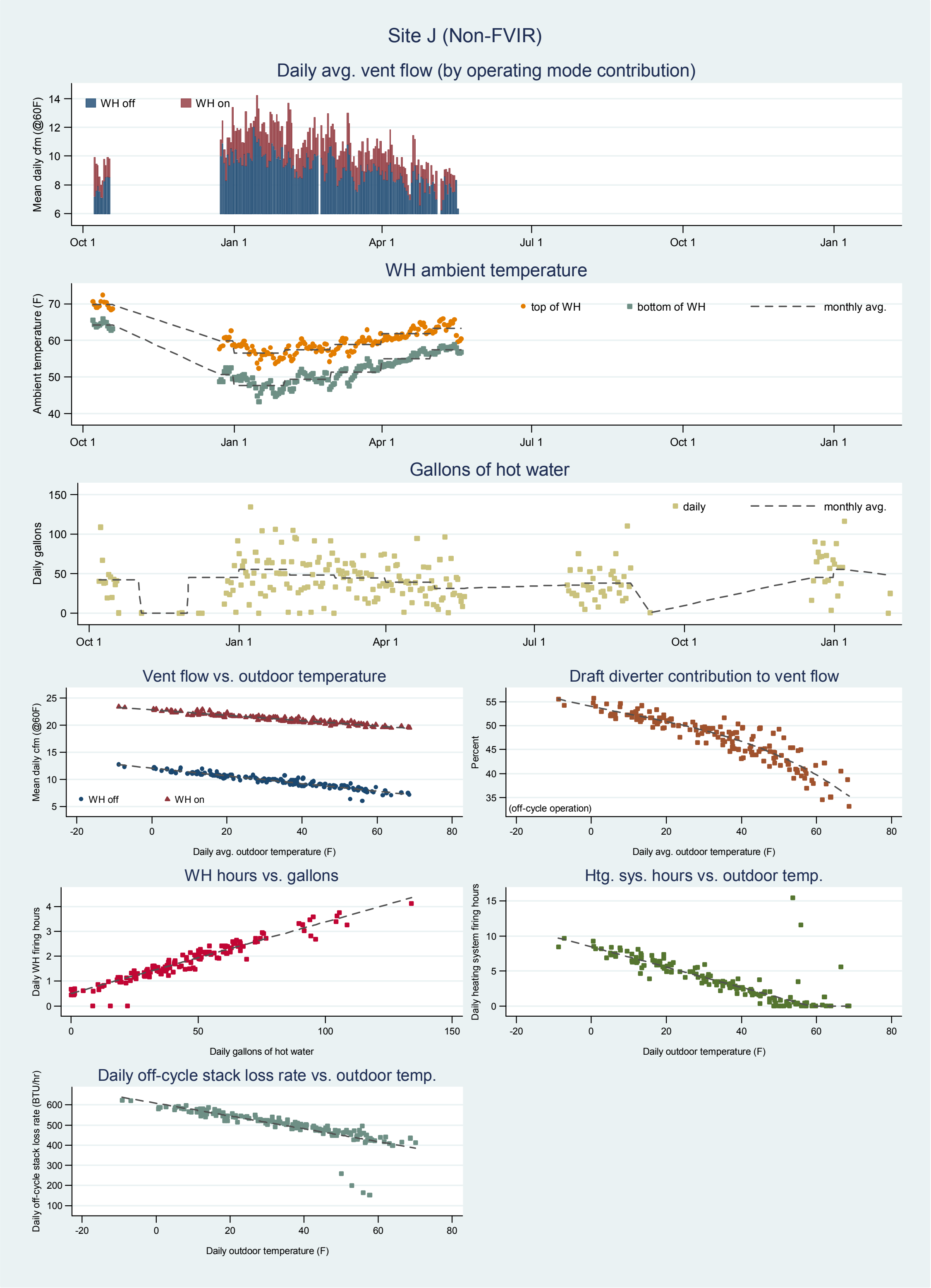
Draft diverter contribution to vent flow

WH hours vs. gallons

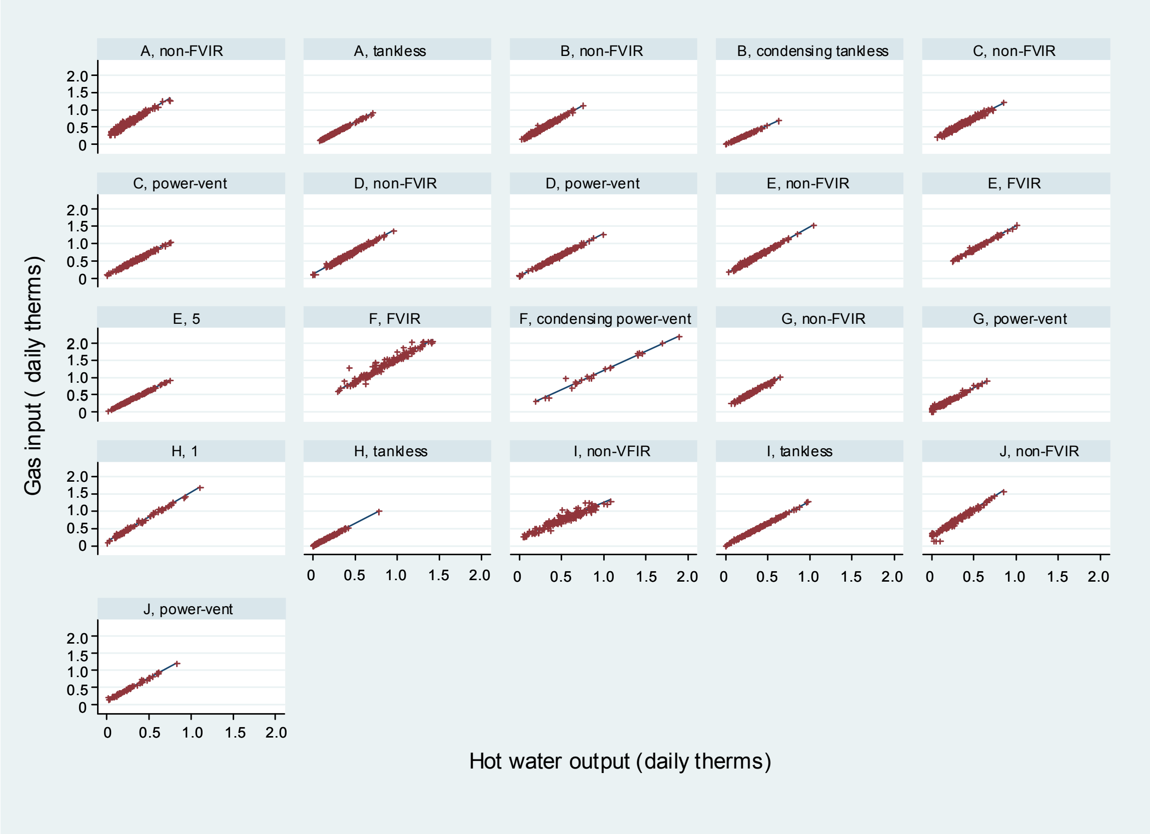
Htg. sys. hours vs. outdoor temp.

Daily off-cycle stack loss rate vs. outdoor temp.


Site I (Non-FVIR)
Daily avg. vent flow (by operating mode contribution)
Mean daily cfm (@60F)
20
15
10
5
WH off
WH on
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
WH ambient temperature
Ambient temperature (F)
75
70
65
60
top of WH
bottom of WH
monthly avg.
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
Gallons of hot water
Daily gallons
200
150
100
50
0
daily
monthly avg.
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
Vent flow vs. outdoor temperature
Mean daily cfm (@60F)
25
20
15
10
5
WH off
WH on
0
20
40
60
80
Daily avg. outdoor temperature (F)
Draft diverter contribution to vent flow
Percent
70
60
50
40
30
(off-cycle operation)
0
20
40
60
80
Daily avg. outdoor temperature (F)
WH hours vs. gallons
Daily WH firing hours
4
3
2
1
0
0
50
100
150
200
Daily gallons of hot water
Htg. sys. hours vs. outdoor temp.
Daily heating system firing hours
15
10
5
0
0
20
40
60
80
Daily outdoor temperature (F)
Daily off-cycle stack loss rate vs. outdoor temp.
Daily off-cycle stack loss rate (BTU/hr)
550
500
450
400
350
0
20
40
60
80
Daily outdoor temperature (F)


Site J (Non-FVIR)
Daily avg. vent flow (by operating mode contribution)
Mean daily cfm (@60F)
6
8
10
12
14
WH off
WH on
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
WH ambient temperature
Ambient temperature (F)
40
50
60
70
top of WH
bottom of WH
monthly avg.
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
Gallons of hot water
Daily gallons
0
50
100
150
daily
monthly avg.
Oct 1
Jan 1
Apr 1
Jul 1
Oct 1
Jan 1
Vent flow vs. outdoor temperature
Mean daily cfm (@60F)
5
10
15
20
25
WH off
WH on
-20
0
20
40
60
80
Daily avg. outdoor temperature (F)
Draft diverter contribution to vent flow
Percent
35
40
45
50
55
(off-cycle operation)
-20
0
20
40
60
80
Daily avg. outdoor temperature (F)
WH hours vs. gallons
Daily WH firing hours
0
1
2
3
4
0
50
100
150
Daily gallons of hot water
Htg. sys. hours vs. outdoor temp.
Daily heating system firing hours
0
5
10
15
-20
0
20
40
60
80
Daily outdoor temperature (F)
Daily off-cycle stack loss rate vs. outdoor temp.
Daily off-cycle stack loss rate (BTU/hr)
100
200
300
400
500
600
-20
0
20
40
60
80
Daily outdoor temperature (F)

APPENDIX H — INPUT/OUTPUT REGRESSION RESULTS



Site	Water heater	Slope term	Std. error	Offset term	Std. error
A	non-FVIR	1.443	0.021	0.25871	0.00565
A	tankless	1.262	0.003	0.01278	0.00108
B	non-FVIR	1.350	0.010	0.11133	0.00298
B	condensing tankless	1.084	0.004	0.00770	0.00102
C	non-FVIR	1.262	0.014	0.13050	0.00533
C	power-vent	1.233	0.010	0.10116	0.00373
D	non-FVIR	1.334	0.009	0.11686	0.00369
D	power-vent	1.218	0.007	0.07175	0.00298
E	non-FVIR	1.359	0.010	0.13032	0.00372
E	FVIR	1.337	0.016	0.17346	0.00928
E	tankless	1.209	0.004	0.01489	0.00130
F	FVIR	1.295	0.024	0.25174	0.02120
F	condensing power-vent	1.108	0.034	0.09833	0.03532
G	non-FVIR	1.328	0.016	0.15153	0.00527
G	power-vent	1.253	0.016	0.07784	0.00312
H	non-FVIR	1.417	0.013	0.12250	0.00544
H	tankless	1.269	0.006	0.01148	0.00109
I	non-FVIR	1.004	0.025	0.24232	0.01420
I	tankless	1.270	0.004	0.02352	0.00168
J	non-FVIR	1.543	0.024	0.28007	0.00839
J	power-vent	1.288	0.015	0.12907	0.00502