IMPACT OF PILOT LIGHT MODELING ON THE PREDICTED ANNUAL PERFORMANCE OF RESIDENTIAL GAS WATER HEATERS

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ABSTRACT

Modeling of residential water heaters via dynamic simulation models can provide accurate estimates of their annual energy consumption if the units' characteristics and use conditions are known. Most gas storage water heaters (GSWHs) include a standing pilot light. It is generally assumed that the pilot light energy will go toward making up standby losses and have no impact on the predicted annual energy consumption. However, that is not always the case. The gas input rate and conversion efficiency ($\eta_{conv,pilot}$) of a pilot light for a GSWH were determined from laboratory data. It is noteworthy that $\eta_{conv,pilot} \approx \eta_{conv,main\ burner}$. The data were used in simulations of a typical GSWH with and without the pilot light, for two cases: 1) the GSWH is used alone; and 2) the GSWH is the second tank in a solar water heating system. The sensitivity of wasted pilot light energy to annual hot water use, climate, and installation location was examined. When the GSWH was used alone there was a slight increase in energy consumption when the water heater was located in unconditioned space in a hot climate. When the GSWH was used as a backup to a solar water heater, cases with a pilot light used up to 80% more auxiliary energy than those without in hot, sunny locations, due to increased tank losses. This demonstrates that the pilot light needs to be modeled for gas storage water heaters to ensure accuracy in all situations, particularly in models used to rate solar water heaters.

1. INTRODUCTION

Dynamic modeling of residential water heaters can predict the expected energy consumption of a water heater, if the unit's characteristics and use conditions are known. While the ratings tests for conventional WHs provide some information, they only test performance under certain conditions. For most water heaters, the efficiency is rated via the Energy Factor (EF) test, which provides the water heater efficiency under prescribed mains water temperature, ambient air conditions, temperature setpoint, and a specific 24 hour draw profile consisting of one draw an hour for the first 6 hours followed by a standby period (1). The actual efficiency and energy consumption of a water heater will vary depending on the actual mains water temperature, ambient air temperature, set point, and draw profile. While dynamic simulations can provide more accurate predictions of the annual water heater performance, the simulations can be time consuming to set up and perform. They also require some simplifying assumptions about the water heater performance, including an assumed hot water usage profile, which is highly variable from household to household.

For solar water heaters (SWH), ratings are done via dynamic simulations by the Solar Rating and Certification Corporation (SRCC) based on its OG300 guidelines (2). The SRCC ratings are based upon component measurements (including collector, tank, and heat exchangers), which provide the inputs to a well-validated component-based simulation model (TRNSYS (3) is used). The simulations provide annual efficiency and potential energy savings for every rated solar water heating (SWH) system at different sites across the country. This provides significantly more information about the likely performance of this water heater than the EF test, although these ratings are done for only one assumed set of use conditions.

One simplifying assumption typically made for residential gas storage water heaters (GSWHs), including those used for rating solar water heaters, is that the pilot light does not need to be explicitly modeled. In cases where the pilot light is not modeled, it is assumed that all the energy consumed by the pilot light goes to offsetting standby losses. Modeling the pilot light slows the rate at which the tank temperature drops during standby and reduces the number of times the main burner needs to fire. So, assuming the pilot light does not need to be explicitly modeled leads to underestimating the time between cycles recovering from standby losses. It is also assumed that the efficiency of the pilot is equal to that of the burner ($\eta_{conv,pilot} = \eta_{conv,main\ burner}$). If this were not the case, the energy consumed by the pilot to offset standby losses would not be equal to the calculated energy consumed by the main burner to offset standby losses in the pilotless model. The implicit assumption is also made that the pilot light will not cause significant overheating of the tank, which is actually only true in some cases.

To determine the impact of explicitly modeling the pilot light on the predicted annual energy consumption of a GSWH (either used by itself or as a backup for a solar water heater), simulations were performed both with and without a standing pilot light. Laboratory data (4) was used to determine the pilot light gas input rate and $\eta_{conv,pilot}$. Once the necessary pilot light parameters were determined, annual simulations were performed for a residential GSWH both with and without a pilot light in several locations across the country installed in conditioned and unconditioned space and at several different hot water usage levels. Simulations were also performed for the same GSWH with and without a pilot used as the backup tank in a two tank SWH system.

2. PILOT MODEL PARAMETER DERIVATION

To include the pilot light into annual simulations of a GSWH, the necessary model parameters (efficiency and burn rate) need to be derived. To do this, time-series data from an EF test of a minimum efficiency 40-gallon gas storage water heater with a pilot light was analyzed (4). The time series data includes tank temperatures at 6 locations and the gas input rate. The static data includes the energy factor EF, the recovery efficiency RE, and the measured tank volume. During the recovery period after the final draw, the pilot light was the only source of heat and the tank temperature slowly decayed due to standby losses, as shown in Fig. 1. The tank energy balance during the standby period is given in Equation 1:

$$C\frac{dT_{tank}}{dt} = \dot{Q}_{pilot,tank} - UA(\Delta T_{tank-amb}) \qquad (1)$$

It can be seen that the rate of average tank temperature decay depends on both the overall heat loss coefficient (UA) of the tank and the heat input rate of the pilot light ($\dot{Q}_{pilot,tank}$). The pilot light input rate is:

$$\dot{Q}_{pilot,tank} = \eta_{conv,pilot}\dot{Q}_{pilot,cons} \qquad (2)$$

The UA value for the tank was inferred from the overall results of the EF test using published algorithms (5). The UA is calculated as:

$$UA = \frac{\frac{RE}{EF}-1}{(\Delta T_{tank-amb})\left(\frac{t_{test}}{Q_{load}}-\frac{1}{Q_{burn}\cdot EF}\right)} \qquad (3)$$

This leaves the pilot light efficiency as the only unknown.

To calculate the efficiency of the pilot light, a model of this particular water heater was created. Modeling was done using TRNSYS, a modular energy simulation environment (3). Simulations of the standby period were performed with different amounts of heat from the pilot entering the tank. The efficiency can be determined by finding the input rate from the pilot to the tank that minimized the difference between the measured and modeled average tank temperatures. The measured and modeled average tank temperatures for the pilot light input value that provided the best fit are shown in Fig 1.

For this particular unit, the measured pilot light burn rate was 480 Btu/hr (506 kJ/hr) and the calculated rate of heat input to the tank was 361 Btu/hr (380 kJ/hr), giving a calculated pilot light conversion efficiency of 75.2%. To compare the pilot light efficiency to the main burner, the main burner efficiency was inferred from the EF data. This unit had a measured recovery efficiency of 75.5%. The conversion efficiency of the main burner is inferred using:

$$\eta_{conv,main\ burner} = RE + \frac{UA\Delta T_{tank-amb}}{Q_{burn}} \qquad (4)$$

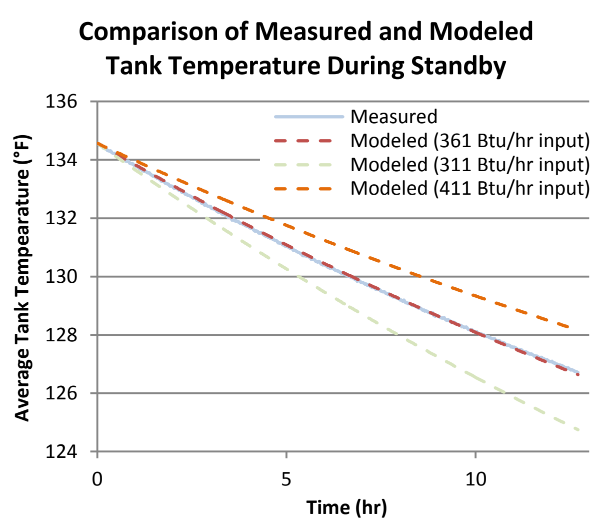

Fig 1. Average measured tank temperature and several modeled temperatures for the standby period of the EF test.

The calculated main burner conversion efficiency was 77.1%. The measured pilot light efficiency is slightly lower than the combustion efficiency of the unit; however, the uncertainty in the pilot efficiency is larger than the difference between the pilot and burner efficiency. This result indicates that the assumption $\eta_{conv,pilot} = \eta_{conv,main\ burner}$ is reasonable (although only one water heater was analyzed, this was a typical unit and there is no reason to suspect this may not be true for other GSWHs), and explicitly modeling the pilot light may not have a significant impact on the annual energy consumption of a GSWH. For the simulations performed here, the pilot light efficiency was assumed to be the same as the combustion efficiency.

The uncertainty in EF, RE, and UA were calculated by propagating the error in the measured data and the uncertainty in the pilot light efficiency calculation is given in TABLE 1. To calculate the impact of the uncertainty of UA on the $\dot{Q}_{pilot,tank}$, simulations of the tank with a UA value equal to the calculated value plus the uncertainty were performed. The largest source of uncertainty in the pilot light efficiency calculation is the uncertainty in the calculated UA. Ideally, addition lab testing work will be performed to provide a more directly measured UA with less uncertainty to ensure there is no significant difference between the pilot light and main burner combustion efficiencies.

TABLE 1: UNCERTAINTY IN PILOT LIGHT CALCULATION

Variable	Value and Uncertainty
$\dot{Q}_{pilot,cons}$	6182 ± 30.9
EF	0.568 ± 0.0122
RE	0.756 ± 0.00545
UA	9.095 ± 0.846
$\eta_{cons,pilot}$	0.752 ± 0.112

3. ANNUAL SIMULATION PARAMETERS

To determine what impact modeling the pilot light had on the predicted annual energy consumption of a gas storage water heater, simulations were performed of a GSWH both with and without a pilot light in a variety of scenarios. To determine what regional differences may exist in the impact of the pilot light, simulations were performed for six different cities: Chicago, IL; Seattle, WA; Atlanta, GA; Los Angeles, CA; Houston, TX; and Phoenix, AZ. These particular cities were chosen as representing the different Building America climate zones (6) as shown in Fig 2.

Water heaters were modeled both in conditioned and unconditioned space to determine what impact installation location may have. A whole home was modeled in this study, which allowed realistic ambient air temperatures to be used for all locations. The buildings modeled here are 2500 ft^2, two story homes with an attached garage. The building envelope and HVAC equipment is consistent with what is used in Building America Benchmark homes (7) and reflects current building practices. The building envelope changes with climate to reflect code requirements and is consistent with IECC 2009 standards (8). The foundation type for each home was selected based on common construction practices in each state (9). Homes in Atlanta, Chicago, and Seattle had basements, while those in Los Angeles, Phoenix, and Houston have slab on grade foundations. For this study, water heaters located in unconditioned space were modeled in the basement if a home had one and the garage otherwise. A more detailed description of the building models is provided in (10).

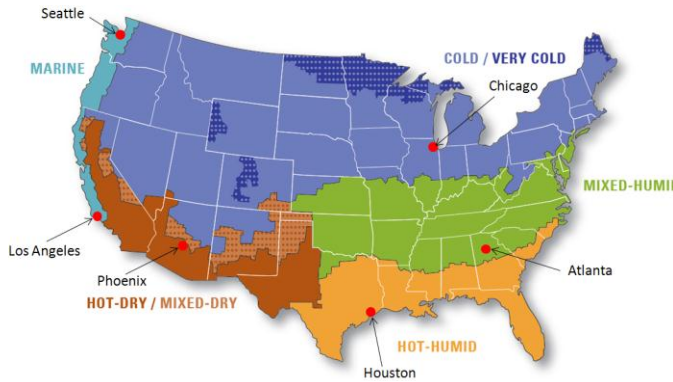

Fig 2. Building America climate zones (2) and the representative cities chosen for this study

Several different hot water usage levels were considered here. The draw profiles used for this study were generated using the Building America Domestic Hot Water Event Schedule Generator (DHWESG). The DHWESG is a statistical tool that generates a full year of discrete events based on a probability distribution of draw events corresponding to the distributions of hourly hot water end uses included in the Building America House Simulation Protocols (11). An example of a daily draw profile from the DHWESG is shown in Fig 3.

Specifying a tempered water flow rate as opposed to the hot water flow rate implies that the amount of hot water drawn will vary with mains water temperature, which leads to different volumes of water being drawn at different locations and, for a given location, different times of the year. The mains water temperature used for each site was calculated based on an algorithm developed at the National Renewable Energy Laboratory (12). For this work, the useful temperature is defined as 105 °F (41 °C) and all water heaters have a set point temperature of 120°F (49 °C).

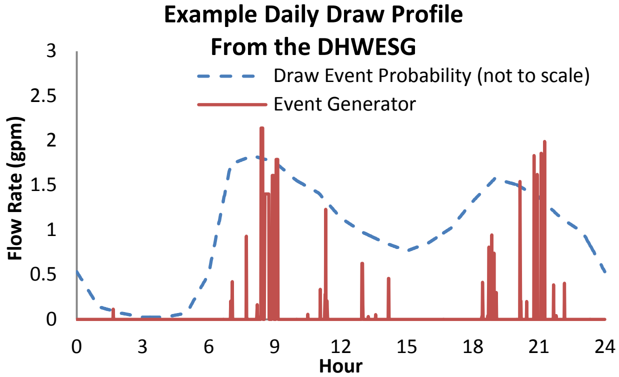

Fig 3: Sample day of draws from the DHWESG

Different annual hot water usage levels were also considered here. The low, medium and high hot water usage levels considered here correspond to 1, 3 and 5 bedroom homes in the Building America Benchmark. Due to the mixed draws, the actual hot water usage level will vary by location as well as draw profile. Annual average hot water usage levels for a GSWH are given in Table 2.

The gas storage water heater modeled here is not exactly the same as the unit that was used to determine the efficiency of a GSWH pilot light. The unit modeled here is a 50 gallon unit with a typical efficiency (EF = 0.60) for a GSWH with a standing pilot. Model parameters for this water heater were derived from ratings data using the same methodology from which the tank UA for the lab tested unit was inferred (5). The pilot light modeled here consumes 450 Btu/h, a typical size for GSWHs (13) and has the same efficiency as the conversion efficiency of the water heater (77.1% for this particular water heater).

In addition to modeling the GSWH alone, simulations of the GSWH used as the backup tank in a two tank SWH system (designed only to meet the DHW load, not for combi applications) were also performed. The solar water heater modeled here is an indirect, active system with flat

TABLE 2: ANNUAL AVERAGE HOT WATER USAGE IN GALLONS PER DAY FOR ALL LOCATIONS AND DRAW PROFILES

	Low	Medium	High
Chicago	36.6	52.2	70.4
Seattle	36.4	51.9	70
Atlanta	34.3	48.9	65.8
Los Angeles	34.4	49	66
Houston	32.5	46.3	62.2
Phoenix	29.6	41.8	56.1

plate collectors. A schematic of the solar water heating system is provided in Fig 4 and relevant model parameters are provided in Table 3.While the optimal system sizing will vary significantly with location and annual hot water use, only one size system was modeled here.

Modeling only one solar water heater in all situations leads to the system being somewhat oversized in low load situations with a large solar resource (Phoenix) and undersized in high load situations for locations with a low solar resource (Seattle). While the system is not optimized for each location, it should be noted that the SRCC provides OG300 ratings for all systems in all locations, even those where a system is significantly oversized or undersized (2). Allowing the system to be oversized in some locations and undersized in others allows for the impact of modeling a pilot light in those particular situations to be studied.

TABLE 3: SWH SYSTEM PARAMETERS

Collector	
Area	5.9 m^2 (64 ft^2)
Orientation	Due south at 6:12 pitch (26.5°)
Solar Tank	
Nominal Volume	0.303 m^3 (80 gal)
U Value	0.573 W/m2-°K
Piping	
Net Length	15.2 m (50 ft)
U Value	1.9 W/m^2-°K

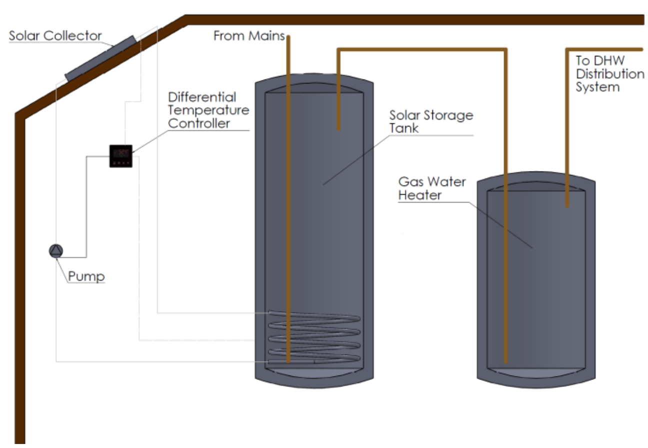

Fig 4: Solar water heater modeled in this study

4. GSWH PILOT LIGHT RESULTS

The percent increase in the annual energy consumption of a GSWH seen from including a pilot light is provided in Fig 5 and the annual energy consumption for each case with a pilot light is shown in Fig 6. While there is always some increase in energy consumption associated with modeling the pilot light, the increase is small (<1%) in most cases. The only cases where the increase in energy consumption starts to become significant is in unconditioned space in hot climates, particularly for the lower use cases.

Explicitly modeling a standing pilot can have two major impacts on the annual energy consumption of the water heater. Because the pilot runs continuously, consuming 450 Btu/h for the full year (8760 hours), there is a minimum energy consumption of 39.4 therm/yr (1154 kWh/yr) for all GSWHs with standing pilots. However, this energy is not generally wasted in a regular gas storage water heater since it offsets standby losses. The pilot light heats the tank constantly at a rate of 347 Btu/hr (366 kJ/hr) and assuming that the tank is isothermal, the rate of heat losses for the water heater would be given by Equation 5.

$$\dot{Q}_{tank,amb} = (UA)\Delta T_{tank-amb} \qquad (5)$$

For nominal conditions of a 120°F storage tank in a 70°F room with this particular water heater (which has a UA value of 8.4 Btu/hr-F [4.4 W/°K]), the rate of tank losses will be about 420 Btu/hr (443 kJ/hr). In this case, the heat added to the tank from the pilot light is less than the standby losses and reduces the rate at which the tank cools, leading to longer periods between when the burner needs to fire to make up standby losses. Equation 5 can also be solved for the temperature difference that can be sustained by the pilot light which yields:

$$347\frac{Btu}{hr} = \left(8.4\ \frac{Btu}{hr{\cdot}°F}\right)(\Delta T_{tank-amb}) \qquad (6)$$
$$\Delta T_{tank-amb} = 41.3°F$$

This means that, with no draws, the pilot light alone can keep the tank roughly 40°F (22°C) warmer than the surrounding air. In cases where the temperature difference is > 40°F, the energy used by the pilot goes to making up standby losses and is useful. If the temperature difference is < 40°F, the pilot light will heat the tank above its set point temperature. In this case, some of the pilot light energy is wasted as it goes to overheating the tank and increases the rate of standby losses. Water heaters in conditioned space that is cooled to 76 °F always have a temperature difference > 40°F, so the pilot energy is never wasted by overheating the tank. However, for water heaters in unconditioned spaces in hot climates, the ambient temperature can be high enough to cause the pilot light to heat the tank above the setpoint temperature, leading to the increases in energy consumption shown in Fig 5 for Houston and Phoenix.

Even in cases of water heaters in conditioned spaces or water heaters in unconditioned spaces in colder climates,

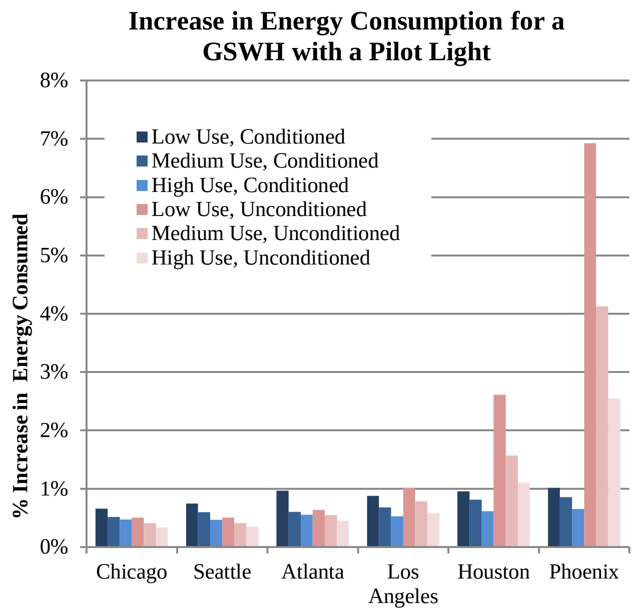

Fig 5: Increase in annual GSWH energy consumption from the inclusion of a pilot light

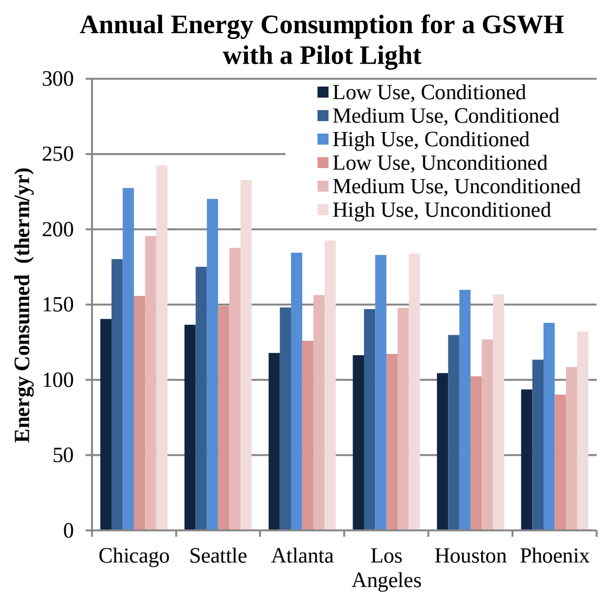

Fig 6: Annual energy consumed by a GSWH with a pilot light

including a pilot light caused a slight increase in the annual gas consumption of the water heater because tank losses increased; the pilot light caused the average tank temperature during standby periods to be slightly higher than in tanks without standing pilot lights. In cases where there is a pilot light, the tank cools more slowly and it takes a much longer time (more than 24 hours) for the burner to fire to make up standby losses. This means that for several hours after a

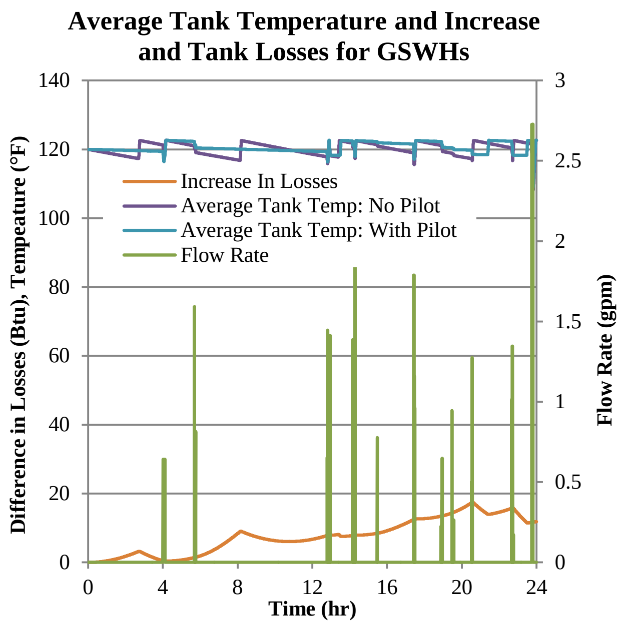

Fig 7: Average tank temperatures and differences in standby losses for units with and without pilot lights

draw, the average temperature and tank losses for a GSWH with a pilot light will be higher than for a unit without a pilot light. A draw typically forces the burner of the water heater with a pilot light to fire before the unit needs to turn on to make up standby losses, so on average the unit with a pilot light has higher standby losses and consumes slightly more energy than the unit without a pilot light. Fig 7 shows the average tank temperature and difference in standby losses over a one day period for units with and without a pilot light. Careful examination shows that the pilot slightly increases the average tank temperature. This impact can also be seen in the increase of tank losses, which are directly proportional to the temperature difference between the tank and ambient air.

5. SWH PILOT LIGHT RESULTS

The annual energy consumption of the SWH with GSWH backup is shown in Fig 8. For clarity on the impact of the pilot light on the overall energy consumption of the SWH, the energy consumption presented here only takes into account the energy consumed by the GSWH and does not include the electricity consumed by the pump and controller for this SWH. In the most favorable installations for the SWH, the energy consumption approaches the annual amount consumed by the pilot light (39.4 therms), indicating that the main burner very rarely fires in these cases.

When a gas storage water heater with a pilot light is used as a backup for a solar water heater, the increase in energy consumption vs. no pilot may be significantly larger than what was seen without solar, because the SWH provides preheated water, which is often hotter than the setpoint temperature of the tank, to the GSWH. Percent increase in annual energy consumption from the pilot light is shown in Fig. 9. The annual average increase in energy consumption across all situations considered here is about 8 therms (230 kWh) and the largest increase seen is about 23 therms (670 kWh). In the most extreme cases, the energy consumed by the gas storage water heater with a pilot light is over 80% greater than what is seen in cases where the pilot light is not modeled**,** indicating that the pilot light is providing significantly more energy to the GSWH than is required to meet the load. In cases where a gas storage water heater is used as a backup for a solar water heater, hot water from the solar storage tank enters the tank during draws. If this preheated water brings the average gas storage water heater tank temperature over the set point temperature (which often happens in summer when the solar storage tank has been charged by the collector loop), the pilot light energy keeps the tank overheated for a longer period, which increases the standby losses. This leads to additional wasted energy in all cases where a GSWH is used as a backup to a SWH.

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

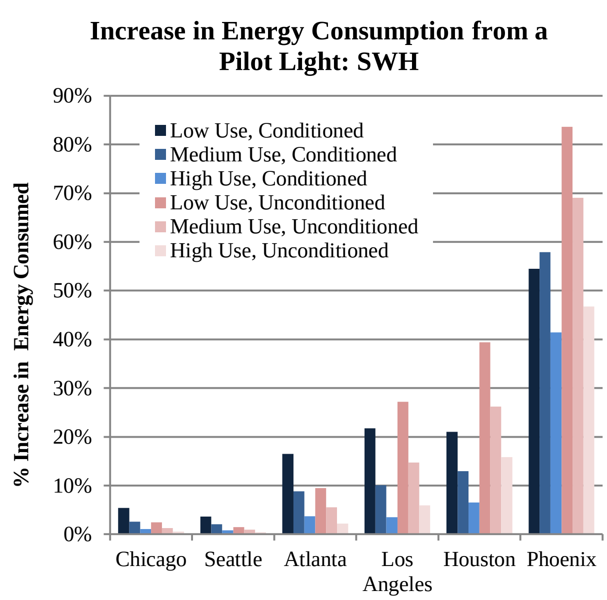

Fig 8: Increase in annual modeled solar water heater energy consumption from the inclusion of a pilot light

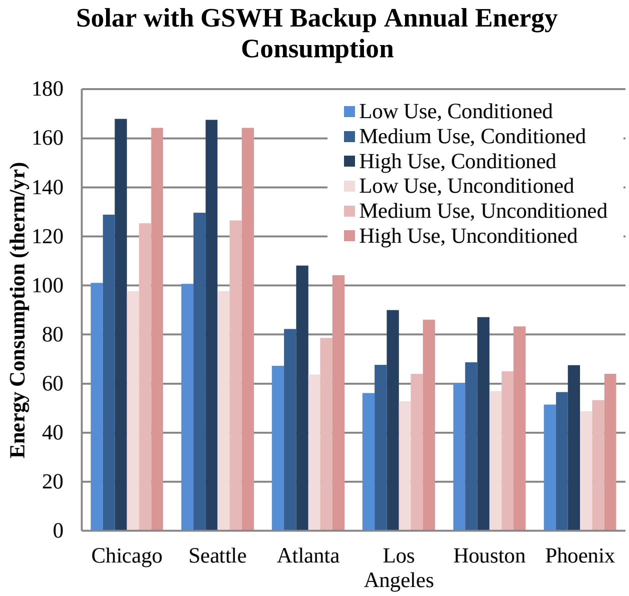

Fig 9: Annual energy consumption of a SWH with GSWH backup

While the increase in energy consumption is generally larger for lower use cases, the low use conditioned space case in Phoenix does not follow this trend: this case does not waste more energy than the medium use case. To help illustrate what is happening in this case, monthly increases in energy consumed for Phoenix are provided in Fig 10. In this particular case, the solar water heater is oversized for the available solar resource which means that the gas burner does not need to fire to meet the water heating load during several summer months. During these months, the amount of wasted energy is driven by how often the gas storage water heater is charged by the solar storage tank because the water in the storage tank is hotter than the setpoint temperature. The unit is charged every time there is a draw, so at lower draw volumes less energy is wasted during these months and more of the energy consumed by the pilot light is useful. This only happens in conditioned space since the high ambient air temperature in unconditioned space during these months leads to a large portion of the pilot light energy usage during this time overheating the tank, similar to what was seen in the case of a GSWH alone.

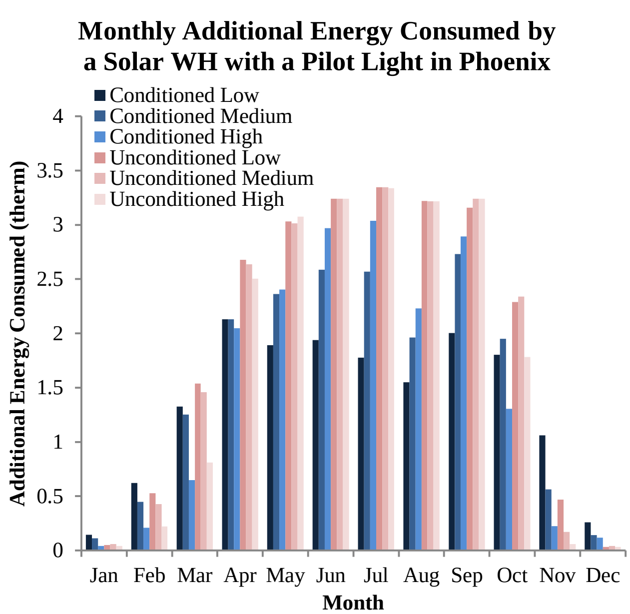

Fig 10: Monthly increase in site energy consumption from modeling a pilot light for Phoenix

6. CONCLUSIONS

The efficiency of the pilot light on a gas storage water heater is approximately equal to that of the main burner, making the assumption that $\eta_{conv,pilot} \approx \eta_{conv,main\ burner}$ reasonable for most simulations. For typical GSWHs, the error associated with not explicitly modeling the pilot light is small (<1 %) in most cases, demonstrating that the pilot light does not need to be modeled in these scenarios. However, when the water heater is modeled in unconditioned spaces that may reach high temperatures, explicit modeling of the pilot light is necessary to capture any potential overheating of the tank by the pilot light.

For SWHs using a GSWH as a backup, explicit modeling of the pilot light is necessary. A small impact was seen in cases where the SWH is undersized for the load, while in situations where the SWH was oversized, a drastic (>80%) increase in energy use was seen. Since these systems are rated for a variety of locations across the US and the current models used in the rating procedure do not explicitly model the pilot light, it is recommended that the rating procedure is changed to include a pilot light so that more accurate energy saving predictions for these systems are generated.

7. NOMENCLATURE

C	= thermal capacitance of storage tank
EF	= Energy Factor
GSWH	= gas storage water heater
P_{burn}	= main burner power
$\dot{Q}_{pilot,tank}$	= rate of heat addition to the tank by the pilot
$\dot{Q}_{pilot,cons}$	= rate of gas energy consumption by the pilot
RE	= recovery efficiency
SRCC	= Solar Rating and Certification Corporation
SWH	= solar water heater
T_{tank}	= storage tank temperature
t_{test}	= length of the Energy Factor test (24 hours)
UA	= overall heat loss coefficient of the tank

$\Delta T_{tank\text{-}amb}$ = the temperature difference between the tank and ambient air.
$\eta_{conv,pilot}$ = pilot light conversion efficiency
$\eta_{conv,main\ burner}$ = main burner conversion efficiency

8. ACKNOWLEDGEMENTS

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