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Electric Water Heaters as Grid Energy Storage

June 2017

About Flink Energy Consulting

Flink Energy was founded by Ken Dragoon in October 2014 to serve clients addressing issues relating to the transition away from fossil energy. Since its founding, Flink Energy's clients have included Ecofys, Oregon Wave Energy Trust, Utah Clean Energy, Energy Trust of Oregon, Renewable Northwest, Renew Oregon, Union of Concerned Scientists, Physicians for Social Responsibility, Vaisala, and Idaho Conservation League. More about Flink Energy's work and publications can be found on the Flink Energy Consulting web site (www.flinkenergy.com).

Memo

To: Board of Directors

From: Fred Gordon, Director of Planning and Evaluation
Mike Bailey, Engineering Manager
Kenji Spielman, Planning Engineer

Date: October 6, 2017

Re: Staff Response to Electric Water Heaters as Grid Energy Storage Study

Oregon's electric investor-owned utilities–Pacific Power and Portland General Electric–are considering programs to control operating hours of electric equipment, including water heaters, as a tool to reduce utility peak loads. Energy Trust commissioned this study to provide a first level assessment of what energy savings on the grid might be associated with this practice. We limited the scope to a paper study (no lab work or extensive simulations) to first get a sense of the order of magnitude and the direction of the energy use impacts. We pursued this, in consultation with load management staff at PGE, to assess a potentially important area where the respective responsibilities of Energy Trust for energy efficiency and Oregon's investor-owned utilities for load control to manage peak might interact.

The study, though by design limited in scope and complexity, shows us that there may be some modest but substantial savings in the transmission and power delivery system, on the utility side of the meter, from load shifting. Furthermore, the study indicates that substantially increasing tank temperatures to provide the ability to interrupt water heater operation for more hours could significantly increase tank losses and diminish the combined electric system benefits of load shifting. This might suggest that while elevated tank temperatures helps utilities shift load for longer periods of time, which is valuable, the benefits need to be balanced against the disadvantage of increasing customer energy use.

The study also shows us that, at this (intentionally) rudimentary level of analysis, the additional transmission and distribution energy efficiency benefits from load shifting specifically are considerably more modest for heat pump water heaters, as compared to resistance water heaters. This is because current heat pump water heaters use roughly half the energy of resistance water heaters, so there is less load to shift. We view this as a byproduct of the significant benefits to ratepayers from the energy efficiency of these units; much of the load is already removed, so cannot be shifted. Half of the benefit to owners and to the grid are already there without control.

Energy Trust's efficiency mission has been defined by the Oregon PUC to focus on reducing energy use on the customer side of the meter. While the reduced energy use on the grid is of interest as benefits of load management, they are currently the responsibility of the electric utilities. However, Energy Trust is looking for ways to increase the penetration of heat pump water heaters to save energy within our mission. We are closely following utility efforts to develop load management programs for water heaters, and hope that the benefits indicated for heat pump water heaters are sufficient (even if they are less than for resistance water heaters) to provoke interest in coordinated program efforts.

Our next step is to share this modest study's results with PGE and Pacific Power to get their assessment of the study's worth, its findings, and its implications. From there, we will continue to discuss potential collaborative efforts as PGE's and Pacific Power's load management programs for water heaters evolve.

Introduction and Background

The Bonneville Power Administration (BPA) conducted an extensive demonstration project under their Technology and Innovation grant program demonstrating the ability of electric water heaters to provide energy storage and power system balancing services. These services were provided by leveraging the energy storage capability of water heaters to shift water heater load in time. Although end use energy storage tends to get less attention than electrical energy storage (e.g., batteries), the effect on the grid is virtually identical to hydro reservoir storage. Where hydro storage allows operators to select when power is generated, end use storage allows operators to select when power is consumed.

In the BPA project, water temperatures were set as high as 160F to maximize storage capability. Mixing (or “tempering”) valves were used to limit water temperatures at the tap to avoid scalding. This strategy maximized the storage capability of the water heaters and showed the efficacy of water heaters to facilitate renewable energy generation on the power system.

The analysis described here examined three water heater control strategies and their effect on at-site water heater losses along with energy effects on transmission and distribution system losses. Two of the three control strategies relied on increasing water heater temperature, incurring higher thermal standby losses. The third strategy assumed no change in water heater temperature. All three strategies assume some additional power use from the added electronic equipment enabling control and communication with the water heaters.

Each of the control strategies was assumed to be used to transfer water heating electrical demand from periods of highest market prices, to lowest market prices. Such a strategy results in shifting electrical demands from times of relatively high line loadings on the transmission and distribution system to periods of lower line loadings. This suggests that the shift in electrical demand would reduce transmission and distribution system losses, because marginal line losses are higher as a percentage of the line loading when lines are heavily loaded. This paper estimates the line loss savings from shifting the loads.

These analyses were performed for both electric resistance water heaters, and heat pump water heaters. Heat pump water heaters deliver substantially more heat per kWh of electrical input than electric resistance water heaters. As a result, there electrical storage capacity is lower per gallon of storage capacity simply because less electrical energy is involved. A further complication of heat pump water heaters is that their efficiency is affected by the water heater set-point temperature. In other words, the control strategy that raises water heater temperature from 120F to 160F substantially reduces the overall efficiency. This effect was also examined.

1. Overview

The analysis reported here estimates standby losses and power consumption from using the energy storage capabilities of electric water heaters to meet wider grid support purposes. The value of water heaters in providing energy storage is being increasingly recognized as a potential source of flexibility[1] (Hledik, 2016). Although controlling water heaters has been practiced for many decades, renewed interest is occurring partly due to the increasing need for power system flexibility to accommodate growing percentage of system power provided by variable renewable generation such as wind and solar. Another important factor is the decline in cost for what is broadly termed the internet of things. Cost of equipment needed to communicate and control relatively small loads has come down substantially over the past ten years.

Water heater loads are not typically the least expensive option for demand management programs due to the relatively small amount of load at each installation. Nevertheless, the resource is substantial, with somewhere between 39 and 50 million electric water heaters in existing homes[2]. A typical 50 gallon water heater stores about 6 kWh of heat energy, with a power rating of 4.5 kW. If all US water heater heating elements were simultaneously energized, they would consume as much as 225,000 MW of power—three times the currently installed US wind capacity. Closer to home, Portland General Electric and Pacific Power are estimated to serve about 500,000 electric water heaters in Oregon, representing more than 2,000 MW of potentially controllable load.

The functionality of water heater control programs can go beyond peak demand reduction, providing energy storage capability equivalent to other storage technologies. Water heater control programs have demonstrated their ability to provide anywhere from 1 to 20 kWh of storage capability. For comparison purposes, a recently quoted installed cost for lithium ion battery technology was found to be just over $700/kWh (Handmer, 2015)—suggesting the possibility that the cost of accessing water heater storage might compare favorably to battery technologies, despite its distributed nature.

Storage capacity of a typical 50 gallon water heater can provide about 73% of the 8.3 kWh of daily average residential water heater use (Ecotope, 2014). The amount of water heater storage as a fraction of daily use has grown over time, due to a combination of more efficient hot water-consuming appliances (e.g., dishwashers and washing machines), and the lower average occupancy rates of single family residences. The Northwest Power and Conservation Council reports annual residential water heater consumption dropped from 4,700 kWh in 1990 to 3,000 kWh in 2012[3]. While today's 50 gallon water heaters store just under 75% of average daily usage, they stored just under 50% in 1990. Residential customers are far less likely to run out of hot water than in 1990, suggesting that some of the excess storage capability may safely be made available for other purposes.

Accessing more storage capacity (i.e., greater than 1-2 kWh) without adversely affecting hot water demand, may require raising tank temperatures. The present analysis estimates at-site energy losses

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[1] See for example (Hledik, 2016).

[2] (Hledik, 2016) reports 50 million electric water heater. US DOE's Water Heater Market Profile, September 2010 reports "just over 100 million residential water heaters," of which about 39% are electric (US Department of Energy, 2010).

[3] *Capacity Impacts of Energy Efficiency: What We Know and What We Don't Know*, Northwest Power and Conservation Council presentation materials, March 11, 2014.

from (in some cases) increased thermal standby losses and increased energy consumption from control and communication equipment needed to operate the water heaters for grid energy storage.

Energy storage has multiple benefits to the power system—the so-called value stacking.[4] While those benefits largely accrue to utilities and grid operators, the cost of increased at-site consumption likely falls to the consumer. The analysis here quantifies these energy costs in order to formulate mechanisms for potentially making the consumers whole on their contribution to grid energy storage.

In short, this analysis examined:

- I) Standby losses due to raising tank temperatures in energy storage control strategies;
- II) Quantifying changes in losses on the transmission and distribution system from shifting water heater loads to light load hours.
- III) Estimating energy effects of operating heat pump water heaters with varying control strategies.

Control Strategies

Energy effects were quantified for three water heater control strategies:

1) No increase in tank temperature from 120F, with 1 kWh of energy storage capacity[5].
2) Tank temperature increase of 10F to 130F, representing 2 kWh of energy storage capability.
3) Tank temperature of 160F, representing an ability to store at least 6.6 kWh of energy (representing all usage between hours ending 10:00 through 22:00).

The quantifications were undertaken in as general a manner as could be managed under the scope of the present project. Hourly load data for Portland General Electric's (PGE) system was used to gauge potential reductions in in transmission and distribution system losses.

Summary of Findings

The analysis comprised a wide range of assumptions and conditions relating to water heater efficiencies and average transmission and distribution system losses. This section provides a quick reference for the results, reported as ranges representing the variations in base system assumptions. Note that the analysis reported here does not include any cost-benefit assessment.

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[4] See for example: *The Value of Distributed Electricity Storage in Texas*, The Brattle Group for ONCOR, November 2014.

[5] This control strategy is based on the ability to turn off water heaters for a period of time representing 1 kWh of load without adversely affecting end-users' perception of any reduction in hot water availability. This is based on personal conversation with the CEO of Mosaic Power that employs a similar control strategy, and a PGE demonstration project that showed no perception of reduced hot water with a two-hour load interruption during the morning peak (Portland General Electric, 2004).

1. T&D efficiency savings were estimated to be in roughly the same magnitude of incremental energy use of control equipment and standby losses the two lower temperature control strategies, and for the high temperature control strategy with high efficiency water heaters.
2. Incremental Tank losses appeared to largely exceed T&D efficiency savings for the high temperature control strategy (160F) using less efficient water heaters.
3. Load shifting using HPWHs produces a smaller impact on T&D efficiency potential because the baseline energy use is significantly less than electric resistance water heaters, so there is less incremental efficiency to be gained from load shifting. In other words, the T&D efficiency gains are already realized due to the reduced overall energy use.

The results reported for electric resistance water heater storage are tabulated in Table 1.

Table 1 Net annual energy effects of electric resistance water heater controls (parenthetical values represent reduced energy consumption).

Electric Resistance WH Net Annual Energy Effects Storage (per water heater)			
	Control Strategies		
	120F (1 kWh/day)	130F (2 kWh/day)	160F (~6.6 kWh)
[1]Resistive Heater Standby Losses (kWh)	0	21 - 100	126 - 613
[2]Control Equipment (kWh)	25 - 35	25 - 35	25 - 35
[3]T&D System Losses (kWh reductions)	(10 - 19)	(19- 37)	(65 -120)
[4]Net Change in Energy Delivery Requirement (50 gal / 80gal)	(6) - 25	9 - 116	31 - 583

[1]Represents water heaters with EFs ranging from .95 to .85.
[2]Consumption estimate based on the 3 watt reported consumption of the Vaughn Thermal Energy Systems water heater controller.
[3]Represents T&D system average losses ranging from 7% to 11%.
[4]Net Energy Delivery Requirement refers to the net of at-site increased consumption and reduced transmission and distribution system losses.

Due to their great efficiency, heat pump water heaters store fewer kilowatt-hours of electric energy for each gallon of hot water produced. Their overall reduced power requirements to provide hot water means that they also provide savings in power system transmission and distribution lines under normal operation, but this savings is not included in this analysis. Instead, this analysis focuses on the additional savings associated with these control strategies. In addition, heat pumps operate more efficiently at lower hot water temperatures, resulting in a greater energy penalty to the higher temperature control strategies. The energy effects of heat pump water heater control strategies are summarized in Table 2. Note that heat pump water heaters are assumed to have built in control equipment and thus will not use extra energy for control purposes.

Table 2 Heat pump water heater energy effects (parenthetical values are reductions in energy consumption or losses).

Heat Pump WH Net Annual Energy Effects (kWh per water heater)			
	Control Strategies		
Effect:	120F (0.4 kWh/day)	130F (.9 kWh/day)	160F (~4.1 kWh/day)
Incremental Consumption (50 gal / 80 gal)	0	119 / 145	1,063 / 1,319
[1]T&D System Losses (kWh reductions)	(4-8)	(8-16)	(40-75)
[2]Net Change in Energy Delivery Requirement (50 gal / 80gal)	(4-8)	111-103 / 137 – 129	1,037-1,010 / 1,293-1,266

[1]Represents T&D system average losses ranging from 7% to 11%.
[2]Net Energy Delivery Requirement refers to the net of at-site increased consumption and reduced transmission and distribution system losses.

Conclusions

Both heat pump and electric resistance water heaters represent a potentially efficient means of providing energy storage services to the power grid. Due to their greater efficiency in heating water, the opportunity for energy storage and load shifting in heat pump water heaters is lower. The at-site increase in consumption is also greater for heat pump water heaters operating above the normal temperature set-point, potentially increasing the need for remunerating customers for providing storage services.

For a high EF electric resistance water heater operating at 160F a consumer's electric bill could be higher by $15 per year at a marginal retail rate of $0.10/kWh. The penalty for heat pump water heaters operating at 160 F may be more than $100 per year. There are offsetting benefits to the grid from operating the energy storage, but those benefits would not be seen by the consumer absent some type of remuneration mechanism.

The analysis shows offsetting energy effects on transmission and distribution system losses. Savings on system losses are a small but significant component of water heater energy storage value stacking.

2. Standby Energy Losses

Standby energy losses are thermal losses between the tank and the ambient environment. The amount of energy transferred by conduction across a material is a function of the thermal characteristics of the material and the difference in temperature between the two sides. The rate of energy lost is typically taken to be proportional to a standby heat loss coefficient times the temperature difference. Although standby heat losses involve a more complex process (e.g., involving conduction, convection, and radiation associated with the interconnecting water pipes), this formulation is commonly used to express thermal losses. The analysis below first presents a method for approximating the standby loss coefficient from published values of water heater Energy Factor, and then computes incremental annual standby thermal losses for each 10F increase in tank temperature for water heaters of differing energy factors.

Computing Standby Loss Coefficients from Energy Factor

The standby loss coefficient is expressed as power (watts or BTU/hr) per degree (F or C) temperature difference between the internal tank temperature and the ambient air surrounding the tank. The symbol UA is commonly used to represent standby energy loss coefficients and is representative of the efficiency of a given water heater. Energy lost over a day can be expressed as:

$$Q_{SL} = UA \text{ X } (T_{Tank} - T_{Amb}) \text{ X } 24 \text{ hours} \qquad (1)$$

Where:

Q_{SL} = Daily Standby Loss (BTU or Watt-hours)
UA = Standby loss coefficient (BTU/hr-F or Watts/F)
T_{Tank} = Temperature of water in the tank (F)
T_{Amb} = Temperature of the air surrounding the water heater (F)

The equation in (1) allows a simple calculation of the change of standby losses with changes in internal tank temperature for a set ambient air temperature and standby loss coefficient (UA). The value of UA varies across water heater models depending on the size and level of insulation around the tank. Water heater efficiency standards have increased over time, so there is a range of UA values across both water heater models and vintages.

Table 3 Energy Factor Conditions

Energy Factor (EF) Calculation Conditions

Standard	Value	Units
Volume of Withdrawn water	64.3	Gallons
Tank Temperature	135	Degrees F
Inlet Water Temperature	58	Degrees F
Ambient Air Temperature	67.5	Degrees F

Source: (Lutz, 1998)

Water heaters receive a proxy efficiency rating from the government. These Energy Factor (EF) ratings represent a ratio of energy consumed by the water heater divided by the thermal energy delivered under a specific set of assumptions with respect to inlet water temperature, tank temperature, ambient air temperature and volume of water withdrawn. While EF ratings of water heaters are relatively commonly available, standby energy loss coefficient values are not. Since both quantities represent the overall efficiency of water heater operation, it is reasonable to for there to be a functional relationship between these quantities—necessary to being able to compute the increase in losses from an increase in tank temperature from a published EF rating.

Just such a functional relationship can be derived from an algebraic estimate of water heater energy consumption proposed in *WHAM: A Simplified Energy Consumption Equation for Water Heaters* (Lutz, 1998):

$$Q_{in} = \frac{vol \cdot den \cdot Cp \cdot (T_{tank} - T_{in})}{\eta_{re}} \cdot \left(1 - \frac{UA \cdot (T_{tank} - T_{amb})}{Pon} \right) + 24 \cdot UA \cdot (T_{tank} - T_{amb}) \qquad (2)$$

Where:

Q_{in} = Energy input (consumption) of the water heater (BTU/day)
Vol = Volume of water withdrawn (gallons)
Den = Density of water (8.35 pounds/gallon)
Pon = Power rating of heating elements (BTU/hr)
UA = Standby loss coefficient (BTU/hr-F)
η_{re} = Recovery efficiency (commonly taken to be 0.98 to reflect losses in tank electrical wiring)
T_{Tank} = Temperature of water in the tank (F)
T_{Amb} = Temperature of the air surrounding the water heater (F)

This equation is a path to Energy Factor as the ratio of Q_{in} to Q_{out}:

$EF = Q_{out} / Qin$ (3)

Where:

Q_{in} = Input Energy
Q_{iout} = Thermal energy usage from hot water withdrawal

Substituting the conditions specified for calculating EF (see Table 3) and substituting the approximation for Q_{in} from (2) into (3) and rearranging terms gives and equation for calculating UA from EF:

UA' = 8.445 / EF - 8.617 (4)

Where:

UA' = Standby loss coefficient (watts/F)
EF = Published water heater Energy Factor

The formulation in (4) presents the needed translation between published values of Energy Factor and the resulting effects of changing tank temperature on losses from (1):

Q_{SL} = (8.445 / EF -8.617) X ($T_{Tank} - T_{Amb}$) X 24 hours (5)

Where:

Q_{SL} = Daily standby loss (watt-hours)

The relation in (4) is shown graphically in Figure 1.

Standby Loss Increases Due to Increased Tank Temperature

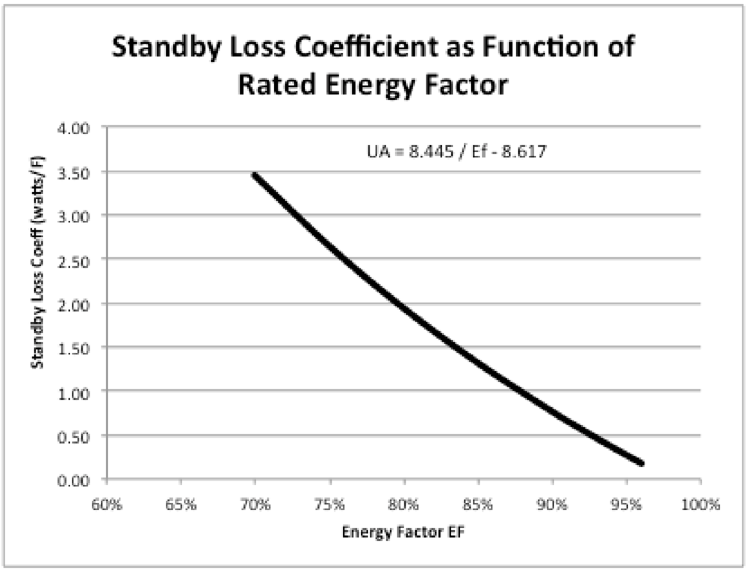

Figure 1 Relationship between EF and standby loss coefficient derived from using the EF rating standards into the WHAM formulation.

Although Equation (4) offers a direct calculation of standby loss coefficients and ultimately standby losses, the fleet of installed electric water heaters represents a range of EF-rated units. Today's electric water heaters boast EF ratings in the 0.95-0.97 range, whereas the minimum standard for 1982 model water heaters was 0.80. The variation in effect ranges over nearly an order of magnitude depending on the water heater efficiency. A modern water heater with EF of 0.95 loses 21 kWh per year for each 10F increase[6] in tank temperature, whereas an older 0.80 EF unit would lose 150 kWh, almost five times as much.

[6] The significance of using 10F is that each 10F increase in temperature represents about 1 kWh of additional energy storage in a 40 gallon water heater tank, just under 1.25 kWh in a 50 gallon tank.

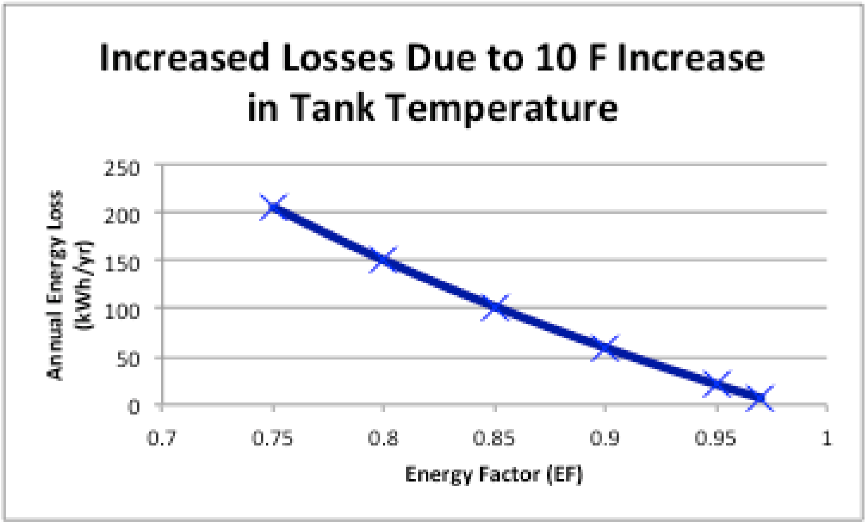

Figure 2 Annual energy losses accruing from increasing tank temperatures as a function of water heater Energy Factor (EF).

Two prominent protocols for operating water heaters for energy storage call for raising the tank temperature 10 F (nominally from 120 F to 130 F), and alternatively 40 F (nominally to 160 F). Increased energy losses from these protocols are estimated in Table 4.

Table 4 Annual Losses from increased tank temperature.

EF	10 F delta (kWh/yr)	40 F delta (kWh/yr)
0.8	150	601
0.9	59	237
0.95	21	84
0.97	6.8	27

Note that in practice the actual losses could be a small fraction of these values depending on the actual operating protocol. The increased losses depend on how long the water heaters are operated at the higher temperatures. For example, if the water temperature is raised by 10 F for half the year, then the losses might be half of the corresponding values in Table 4.

There may also be some other reductions in losses not accounted in the foregoing formulation. Operating protocols call for allowing inlet water to accumulate at the bottom of the tanks in varying amounts for varying amounts of time. This accumulation of cooler water for longer periods would likely have the effect of reducing losses through the bottom of the tank. Those savings are not accounted for here, though they are likely small in comparison.

Despite the limitations of this analysis, it provides perhaps an upper bound on the losses that accrue from control strategies relying on raising tank temperatures. This information will be used as guidance with respect to energy savings in the balance of the system from changing the timing (shape) of water heater loads in subsequent sections of this paper.

3. Effects on Transmission and Distribution Losses

Energy losses over the transmission and distribution (T&D) system as a fraction of the delivered energy are highest when the power flows are greatest. This is due to the resistive losses being proportional to the square of the current flowing in a wire conductor. As a result, T&D losses could be reduced if some of the power demand can be shifted from times when the system is more highly loaded, to times when the system is more lightly loaded (e.g. night).

The report *Valuing the Contribution of Energy Efficiency to Avoided Marginal Line Losses and Reserve Requirements* (Lazar & Baldwin, 2011) lays out a methodology for quantifying such savings and is used here to estimate the savings potential from load shifting out of hours of highest usage to hours of lowest usage.

The report divides T&D losses into two categories: No-load, and resistive losses. Resistive losses occur due to the friction involved in moving electrons in a conductor, and increase with the square of the current flow. The current flow in a power line is proportional to power for a given voltage, so that the resistive losses increase as the square of the power flowing through the conductor. No-load losses are assumed to be present at all times and are not affected by the amount of power delivered.

Making the simplifying assumption that the resistive losses on any hour are proportional to the square of the power transfer[7]:

$$L_{res}(t) = k\, P^2(t) \qquad (6)$$

Where:

- t represents a specific hour
- $P(t)$ is the total power transferred in hour t (in MWh)
- $L_{res}(t)$ is the resistive power losses on hour t (MWh)
- k is a constant of proportionality

Expressing average resistive losses (L'_{res}) as a fraction of total loads delivered:

$$L'_{res} = k\, \Sigma P^2(t) \,/\, \Sigma P(t) \qquad (7)$$

Now expressing total losses as a percentage in terms of no-load and resistive losses:

$$L_{tot} = \alpha L_{tot} + L'_{res} = \alpha L_{tot} + k\, \Sigma P^2(t) \,/\, \Sigma P(t) \qquad (8)$$

Where:

- L_{tot} is total system losses as reported by system operator (fraction of total loads)
- αL_{tot} represents no-load losses—according to (Lazar & Baldwin, 2011) α is typically between 20% and 30%

Substituting (7) for L'_{res} in (8), and rearranging to solve for k:

$$k = (1-\alpha)\, L_{tot}\, \Sigma P(t) \,/\, \Sigma P^2(t) \qquad (9)$$

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[7] The formulation here is consistent with (Lazar & Baldwin, 2011).

The formulation in (9) offers a means of calculating the constant of proportionality from a given system's total average loss percentage (L_{tot}), the no-load loss fraction (α), and a set of hourly loads. Values of k were calculated over a range of values for L_{tot} and α based on Portland General Electric's 2014 hourly loads as reported in its Federal Energy Regulatory Commission (FERC) form 714 filing.

Once the proportionality constant (k) is computed, the change in losses resulting from load shifts can be computed from (8). PGE's FERC Form 714 loads were adjusted by a marginal 10 MW, taken out of selected hour(s) of the day as shown in Table 5. The hours of load reduction were selected to maximize the savings based on PGE's specific load shape as shown in Figure 3 and Figure 4. The year was divided into "winter" (October-March) and "summer" segments (April-September) periods to take advantage of the differing load shapes[8]. While the load reduction periods were allowed to change, the energy removed from those hours was consistently returned on hour ending 03:00. This was due to hour ending 03:00 consistently being the lowest load hour[9].

Table 5 Hours of the day from which load was optimally reduced for different lengths of load reduction periods.

Control Strategy	"Winter" Shift Period (October – March)	"Summer" Shift Period (April-September)
1	18:00-20:00	15:00-17:00
2	17:00-21:00	15:00-19:00
3	06:00-22:00	6:00-22:00

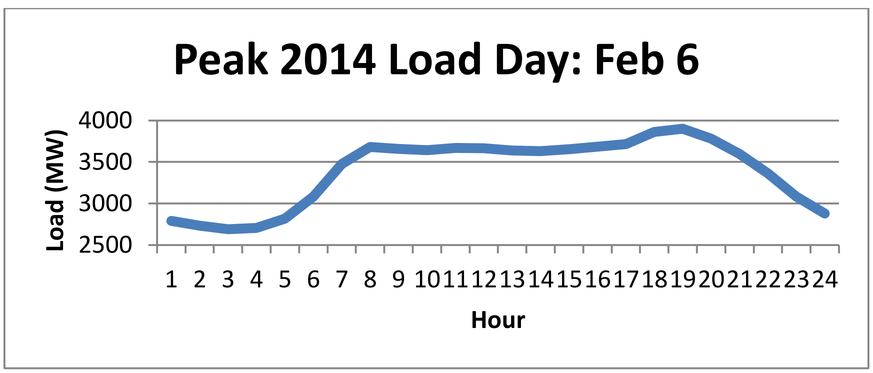

Figure 3 PGE peak winter load day 2014.

[8] In practice the optimal load reduction time segments could be adjusted daily, but that level of sophistication was beyond the scope of this project.

[9] This implicitly assumes that all the load shaped out of the heavier load hours could be returned in one hour. This is likely the case up to about 4 hours of load shift, beyond which the returned energy may take more than an hour to return. Spreading the payback to adjacent hours (i.e. in the 02:00 – 0:400 range) is not expected to change the results significantly as the load in those hours doesn't change very much (i.e., consistently low).

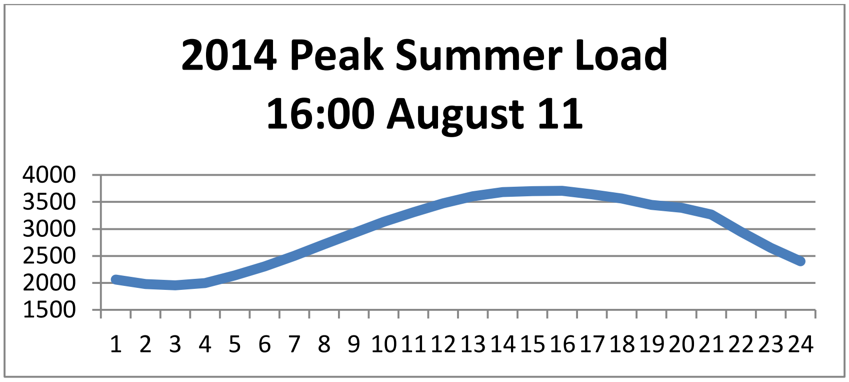

Figure 4 PGE peak summer load day 2014.

Applying the load shifts in Table 5 to PGE's loads and determining the marginal change in losses was done for a range of assumptions and reported in more detail in Appendix A.

Transmission and Distribution System Loss Results

Table 6 shows the energy savings computed for load shifts corresponding to the three control strategies. Results are reported as ranges with the lower savings quantities corresponding to average T&D system losses of 6.5% of power generated and no-load losses constituting 20% of the total losses; and the higher savings corresponding to average system losses of 11% and 30% of them coming from no-load losses. Refer to Appendix A for additional information and data.

Table 6 Marginal transmission and distribution system loss reductions.

Net Annual T&D Loss Effects per water heater (kWh)			
Control Strategy	120F	130F	160F
Electric Resistance Water Heaters	(10 – 19)	(19 - 37)	(65 - 120)
Heat Pump Water Heaters (50 gal / 80 gal)	(4-8)	(8-16)	(40-75)

4. Heat Pump Water Heaters for Energy Storage

Control strategies are contemplated for heat pump water heaters that would potentially have similar effects on the power system: reduced transmission and distribution losses. Heat pump technology presents some important differences with electric resistance water heaters. These stem primarily from the far greater efficiency of the units in heating water, and the dependence of that efficiency on tank temperature. Heat pump water heater efficiency is termed “Coefficient of Performance” (CoP) which is the average heat delivered divided by the electric power supplied.

The CoP enters into the analysis in a couple of ways. In the foregoing electric resistance water heater analysis, the amount of thermal energy shifted was nearly identical to the amount of electrical energy shifted. This relationship is vastly different with the heat pump units—shifting 1 kWh of thermal energy is associated with a much smaller (~.5 kWh at CoP 2) of electrical energy. This resulting “reduction” in storage capacity due to improved efficiency decreases the incremental grid benefits from load shaping compared to a traditional electric resistance unit.

CoP is affected by a number of factors, including the efficiency of the heat pump compressor, tank insulation, usage patterns, ambient temperatures and cold water inlet temperatures. Further complicating matters is that commercial units are commonly equipped with resistance heating elements that are engaged under sets of proprietary conditions (e.g., water flow rate, level of hot water in the tank, etc.). For the purposes of this study, very simplifying assumptions were made in order to arrive at a rough approximation of the capability of heat pump water heaters to participate in water heater control strategies for saving energy. A sample CoP curve was obtained for this analysis[10] shown in Figure 5.

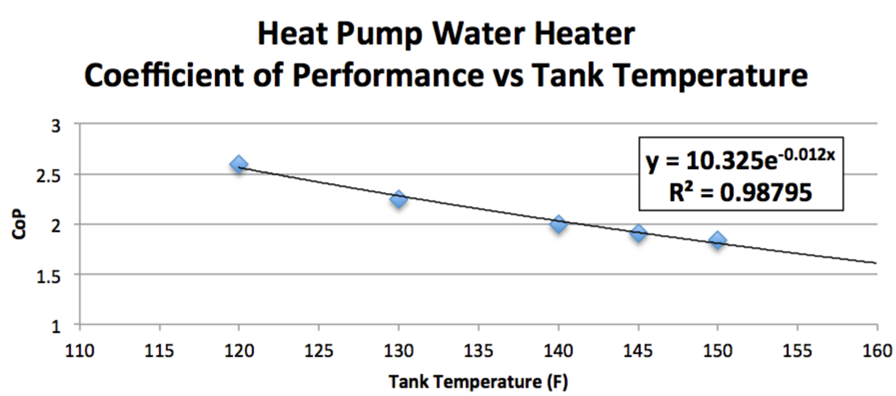

Figure 5 Sample CoP curve used in this analysis.

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[10] Generously supplied via e mail by Mr. Ben Larson of Ecotope based on a General Electric model and assuming 46 gallon per day 3 person draw pattern, and 57F inlet water temperature. Note that these assumptions are not consistent with the EF assumptions used in the electric resistance water heater analysis.

Another important difference between heat pump and electric resistance units is that in addition to increased standby losses from higher tank temperatures, the efficiency of the units (per Figure 5) also degrades. That leads to greater penalties associated with the higher tank temperature control strategies than were assessed for the electric resistance heating units.

Table 7 shows the individual and combined effects of raising tank temperature on standby losses and CoP for the sample heat pump water heater data. There are some important caveats to these results to keep in mind. As previously mentioned, there is no account taken of the algorithm that may at times energize thermal heating elements in preference to the unit's heat pump compressor. The assumption here is that the entire hot water consumption is provided through operating the compressor. In addition, there is no account taken of the time during which the water heater tank is not full of 130F or 160F hot water. As a result, the increased standby losses may be overstated somewhat.

Table 7 Heat pump power consumption changes and average tank temperature.

Changes in Heat Pump Power Consumption[1]

Tank Temp (F)	120	130	160
Standby Losses			
50 gallons-3.5 BTU/hr/F (kWh/yr)	539	629	899
80 gallons-4.5 BTU/hr/F (kWh/yr)	693	809	1155
Average CoP	2.6	2.3	1.6
Total Power Consumption (heat production + stby losses)			
50 Gallon Tank (kWh/yr)	1186	1371	2110
80 Gallon Tank (kWh/yr)	1246	1450	2269
Increase from 120F Case		**130**	**160**
50 Gallon Tank (kWh/yr)		185	924
80 Gallon Tank (kWh/yr)		204	1024

[1]Assumes ambient temperature of 60F, 2500 kWh per year heat withdrawal.

Heat Pump Water Heaters for Grid Storage

Raising tank temperature in heat pump water heaters both increases local standby heat losses and reduces the efficiency of providing hot water generally. This double penalty means that control strategies that rely on raising tank temperatures can lead to net energy losses. Table 8 summarizes the energy costs and benefits from water heater control strategies. The last row shows the net effect of water heater control. The energy storage capability per water heater is lower than for electric resistance water heaters due to less electrical energy inputs corresponding to the same thermal energy storage amounts.

Table 8 Heat pump water heater net energy effects (positive values are increases in consumption, parenthetical values represent decreases in net energy consumption).

Heat Pump WH Net Annual Energy Effects (kWh per water heater)			
Effect:	**120F (.4 kWh/day)**	**130F (.9 kWh/day)**	**160F (~4.1 kWh/day)**
Incremental Compressor Loads (50 gal / 80 gal)	0	90 / 116	899 / 1,155
Standby Losses (assumes .9 EF equivalent)	0	29	164
Total Incremental Demand (assumes .9 EF equivalent insulation levels)	0	119 / 145	1,063 /1,319
[1]T&D System Losses (kWh reductions)	(4-8)	(8-16)	(40-75)
[2]Net Change in Energy Delivery Requirement (50 gal / 80gal)	(4-8)	111-103 / 137 – 129	1,037-1,010 / 1,293-1,266

[1]Represents T&D system average losses ranging from 7% to 11%.
[2]Net Energy Delivery Requirement refers to the net of at-site increased consumption and reduced transmission and distribution system losses.

It needs to be emphasized that the analysis of heat pump water heaters undertaken here is a vast simplification of the complexities of commercially available hybrid (i.e. combined chiller and resistance heat) water heaters. For example, raising the tank temperature may reduce the likelihood of the units energizing their electric resistance heating elements, resulting in a net reduction in overall consumption. The results in Table 8 need to be tested against real world applications.

Comparing Tables 7 and 8 shows that heat pump water heaters may be expected to have lower electrical energy storage capacity for a given tank volume than electric water heaters, and that the higher temperature control strategies result in higher penalties for the heat pump water heaters. This analysis does not consider the transmission and distribution energy savings that result from the reduced energy use of heat pump water heaters compared to electric resistance water heaters – only the potential savings from load shifting.

5. Conclusions

Water heaters appear to represent efficient means of providing energy storage to the power grid. The resource potential is significant given the number of electric water heaters in Oregon. The many system benefits increase with amount of energy storage across the control strategies examined, despite higher energy consumption in the higher storage strategies. If applied over the roughly 500,000 electric water heaters in PGE and Pacific Power Oregon territories, they would could reduce peak load by as much as 200 MW, and provide somewhere in the range of 500-3,000 MWh of storage: a significant resource potential.

Heat pump water heaters show potential as energy storage devices, especially as they will come DR ready. However, increasing tank temperature in heat pump water heaters to provide grid storage introduces increased concerns over customers incurring higher energy charges from this secondary use of their water heaters.

Appendix A: Transmission and Distribution System Loss Savings Charts

The charts in this section present the transmission and distribution loss savings from shifting loads from one time period to another based on Portland General Electric's 2014 load shape, based on a marginal 10 MWh/h shift out of the heavy load hours. Energy removed from the indicated time periods of various lengths were all returned on hour ending 03:00 when loads were lowest. The annual energy savings per water heater increase as the amount of energy (i.e., duration of the event over which loads are reduced) is increased. The figures assume that during the removal hours, all participating water heaters are turned off.

The savings are also dependent on the total transmission and distribution system losses, as well as the breakdown between no-load losses (i.e., fraction of total losses that occur when system is not loaded) and total loads. Each chart presents three curves representing no-load percentages of 20, 25, and 30% over a range of total system losses. The charts vary from one to the next by the duration of the time the water heaters can be turned off. The turn-off start times were optimized for each duration length. Water heater technologies the offer greater storage capability (e.g., higher tank temperatures, bigger tanks) can in principle withstand longer outage durations without affecting users' hot water use.

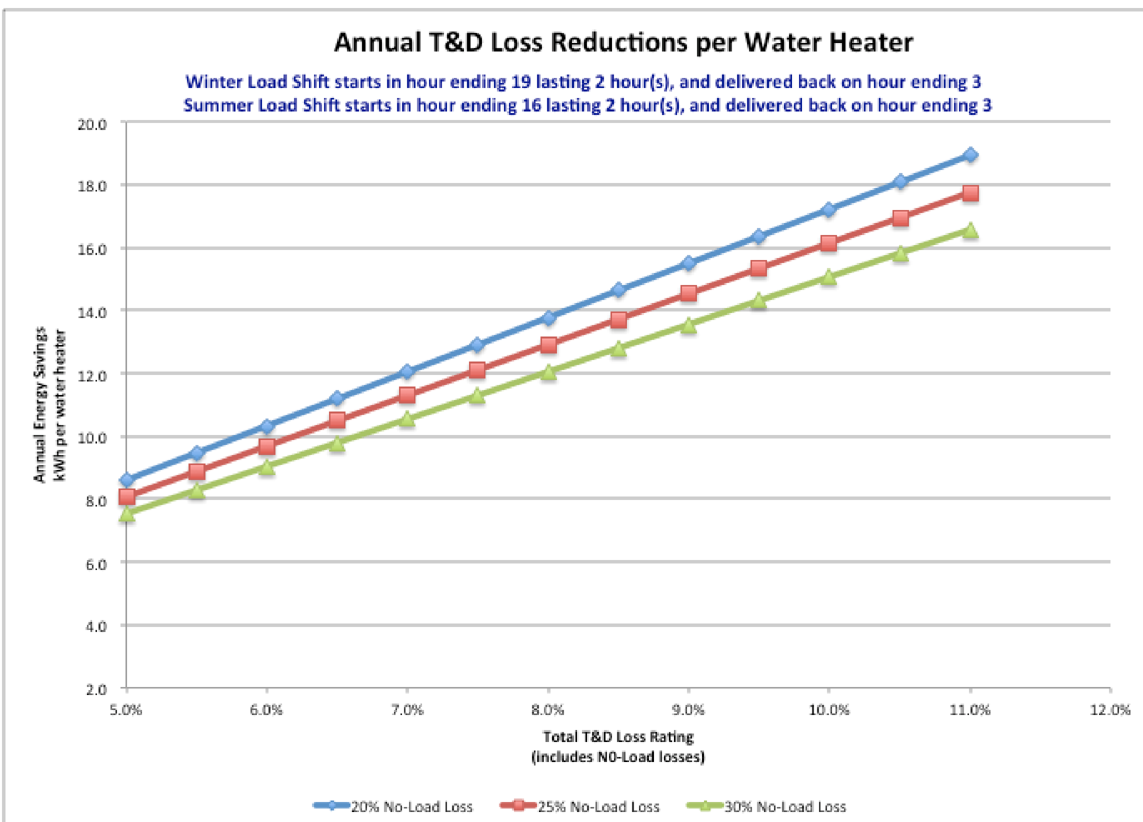

Figure 6 Transmission and distribution system marginal losses for 120F control strategy, corresponding to 1 kWh of storage.

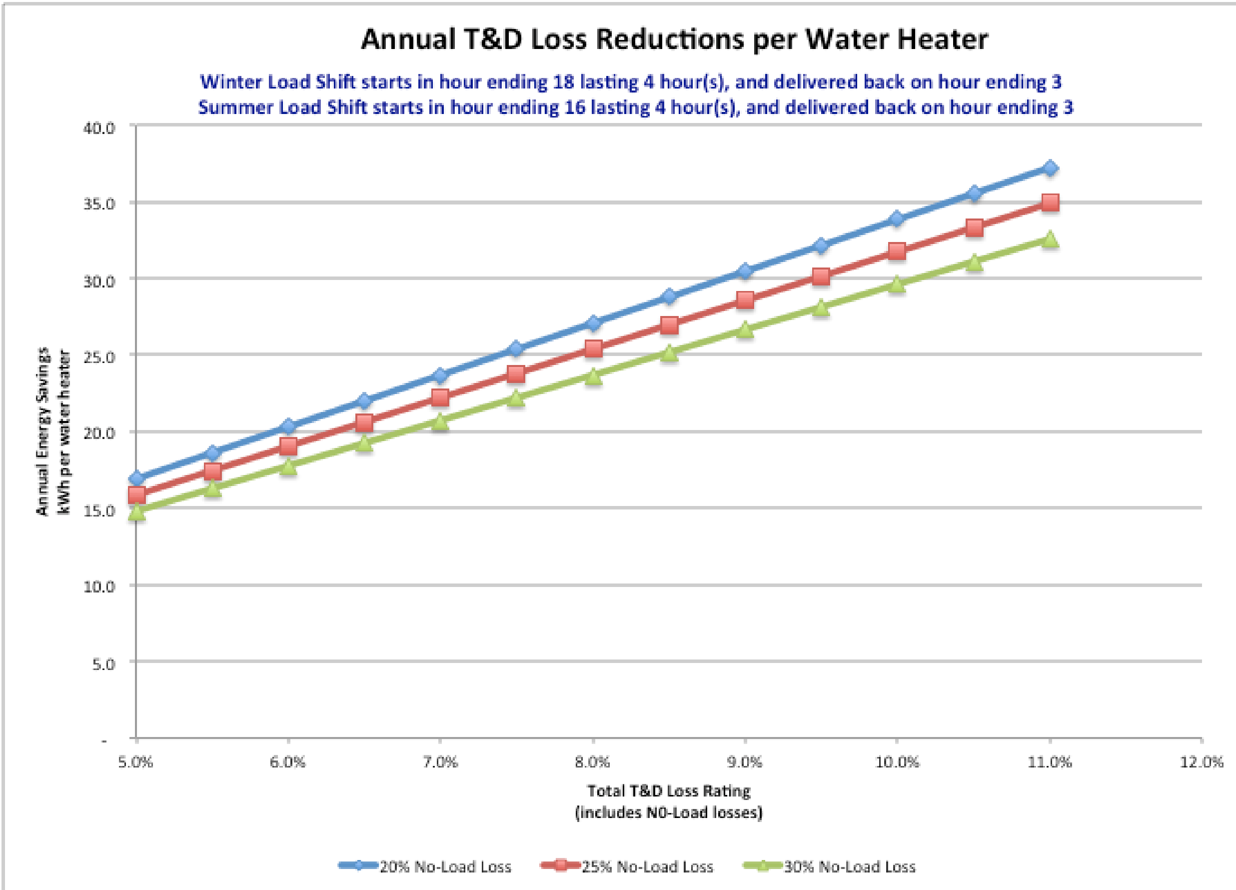

Figure 7 Transmission and distribution system marginal losses for 130F control strategy, corresponding to 2 kWh of storage.

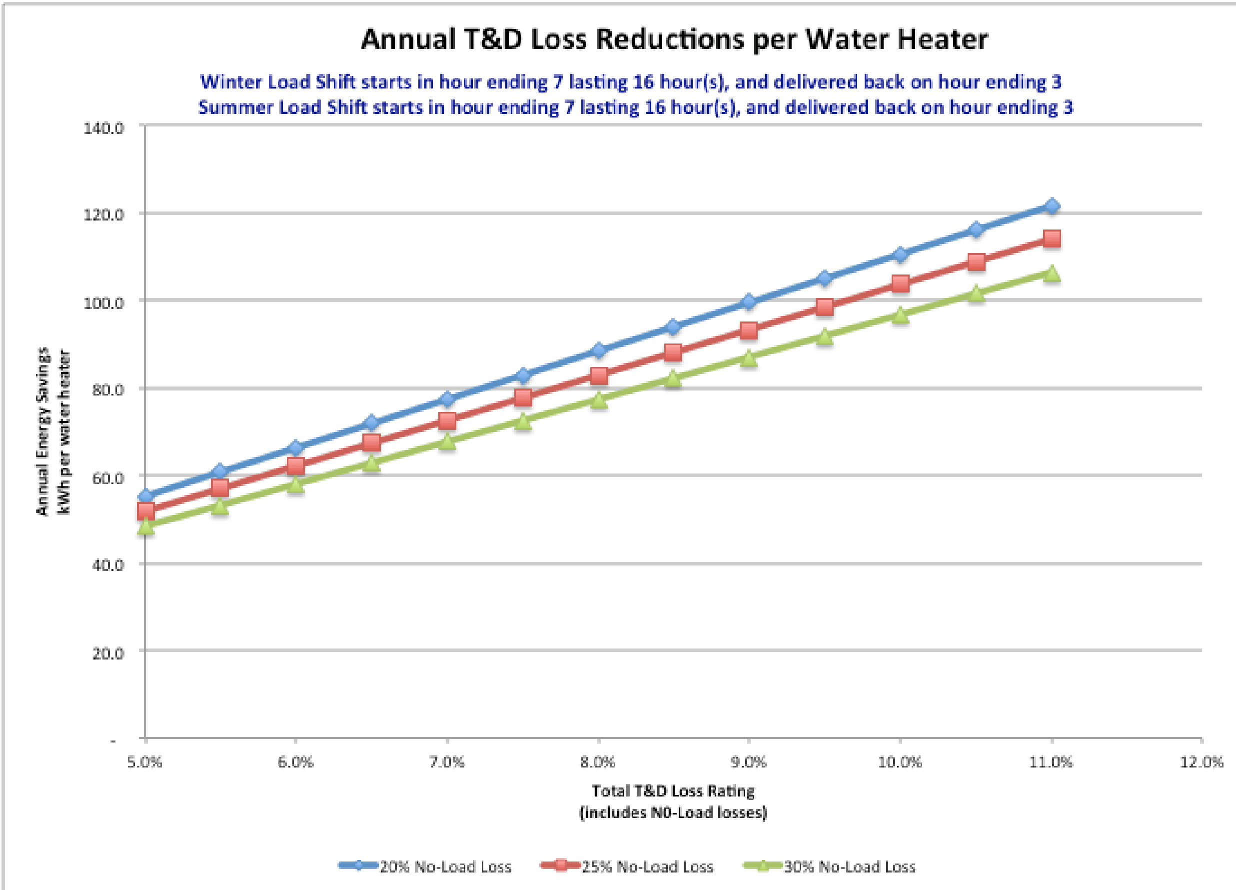

Figure 8 Transmission and distribution system marginal losses for 160F control strategy, corresponding to 6.6 kWh of storage.

Appendix B Further Inquiry

The following is a list of issues that may deserve additional study to refine or expand the work described in this paper:

1) Quantify effects of leaving cold water at the bottom of the tank for longer periods should reduce losses—would be worth estimating on paper, and in the laboratory.
2) Quantify the effects of likely operating protocols on actual losses (e.g., percent of time at higher temperatures, HPWH logic).
3) Perform a cost / benefit analysis for water heater control strategies and equipment.
4) Perform a full power grid analysis at the substation level to more accurately assess distribution system losses for a specific substation or set of substations.
5) Estimate effects on generation supply fuel use and carbon emissions.
6) Project future savings based on all new water heaters having control technology.
7) Conduct field tests of heat pump water heaters to more accurately estimate the effects of temperature controls for energy storage.
8) Apply the same analysis to new, high efficiency trans-critical (CO_2) heat pumps, including space heating applications.

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