Grid Interactive Water Heaters - How Water Heaters Have Evolved Into a Grid Scale Energy Storage Medium

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ABSTRACT

Grid interactive water heating (GIWH) adds bi-directional control to electric resistance water heaters allowing the utility or third party aggregator to rapidly and repeatedly turn them on and off, or incrementally ramp their power up and down. This functionality turns a fleet of water heaters into a flexible energy-storage medium, capable of increasing and decreasing the load on the grid on a second-by-second basis. And GIWHs are currently the least expensive form of energy storage available (Podorson 2014). Utilities can use fleets of grid-enabled water heaters for load shifting, demand response, arbitrage, ancillary services, or to respond to unexpected grid-stabilization events.

Electric resistance water heaters with grid integrated controls are currently available to utility load control or demand response programs. Additionally, more recently introduced retrofit control products designed for the existing water heater install base are also available. One retrofit control product even allows the control of gas water heaters for energy savings and demand response.

Two pilot studies were completed in 2015, both showing positive results and the successful technical demonstration of this technology. More recently introduced retrofit products have yet to be thoroughly vetted. Numerous pilots are slated for 2016 which will showcase how well GIWH products fare in the coming year.

Introduction

Grid interactive water heating adds bi-directional control to electric resistance water heaters allowing the utility or third party aggregator to rapidly and repeatedly turn them on and off, or incrementally ramp their power up and down. Bi-directional control is a powerful tool because it allows a fleet of water heaters to act as a block of flexible load. A fleet of GIWHs can be powered down in times of under-generation, to help relieve a capacity shortage on the grid, or powered up in times of over-generation, to help absorb excess power generation. Water heaters are unique because they're one of the only appliances in a home that can store energy without directly affecting the amenity of the appliance. Turning a water heater on or off has hardly any immediate impact on the comfort of a customer, whereas turning other appliances on or off (such as refrigerators or laptop computers) will directly affect the amenity of the appliance. Traditional batteries supply power when generation is low and absorb power when generation is high. In this way, they help generation follow the load. GIWHs provide exactly the same functionality, but flip this equation, allowing the load to follow generation. In this way aggregated GIWHs act as virtual power plants to quickly and effectively control the amount of power on the grid. Moreover, these fleets are completely scalable and can perform this functionality within seconds (Podorson 2014).

Energy storage doesn't reduce energy consumption, and shouldn't be confused with energy efficiency. Both services can provide environmental and economic benefits, depending on regional generation and transmission characteristics. Electric resistance water heaters

(ERWH) are well suited to fast-responding energy storage because they can be modulated on a second-by-second basis. Heat pump water heaters (HPWH), on the other hand, can't be modulated with the rapidity of an ERWH, and are less suited to fast-responding energy storage. HPWHs do, however, consume significantly less energy than ERWHs, and are well suited to energy efficiency measures.

GIWHs also offer economic benefits. Researchers from the Rocky Mountain Institute estimate that electric utilities plan to invest over $1 trillion in traditional grid infrastructure over the next 15 years. The use of demand-side flexibility – the ability for demand resources to change throughout the day due to market conditions – in the residential sector alone is estimated to be able to save 10-15% of those grid costs. This could cut the customer's electric bill by 10-40%, and can be accomplished with rate structures and technologies that exist today (Dyson et al. 2015).

After five years of uncertainty, large capacity GIWHs (over 55 gallons) are now allowed to be manufactured for use in utility load management and demand response programs. In April 2010, the US Department of Energy (DOE) issued an energy efficiency standard that banned the production of large capacity electric resistance water heaters – the preferred water heater technology for grid integration (DOE 2010). The ruling went into effect on April 16 2015, but due to the long-standing efforts of many stakeholders, the ban was lifted a few weeks later when President Obama signed the Energy Efficiency Improvement Act of 2015 (DOE 2015). The legislation allows manufactures to produce large capacity GIWHs for exclusive use in utility load management and demand response programs.

Benefits to the Utility

GIWHs enable the utility to shift loads, conserve revenue via the arbitrage of wholesale electricity, generate revenue via ancillary services, and keep the grid stabilized during unexpected events. A more detailed description of these features follows:

Load Shifting

Pre- or post- charging of water heaters around peak times can flatten the peak load while maintaining the customer's supply of hot water. This is known as load shifting, or intelligent load control. Instead of simply shedding the peak load, the energy consumption is redistributed to times of lesser demand.

Arbitrage

Utilities or aggregators can perform arbitrage on the wholesale market price for electricity, charging the water heaters when the price is low and discharging them when the price is high, saving themselves and their customer's money. This can be especially useful for cooperatives and municipal utilities where the savings can be passed along directly to the customer.

Frequency Regulation

On a more advanced level, utilities can use GIWHs for frequency regulation or other ancillary services. Frequency regulation - or just "regulation" - is the second-by-second matching of generation to the load. Depending on the market there can be significant revenue potential from regulation. Furthermore, the need for regulation will only increase as more intermittent renewables are put on the grid. Solar and wind power, for example, inherently fluctuate with the availability of sun and wind, and cause generation to spike and dip unexpectedly. Regulation is required to even-out these fluctuations and keep generation matched to the load. Few resources can supply the flexibility needed for this service – generating plants can't generally respond quickly enough, but electric resistance water heaters can perform this service very well.

Grid Stabilization

Perhaps one of the most valuable services that GIWHs provide is the ability to respond to grid stabilization events within seconds. If a transformer trips or another unexpected event occurs, GIWHs allow the utility to shed or increase load very quickly.

Valuing Utility Benefits

Until recently the economic benefits of the aforementioned services were difficult to determine. First, detailed water heater modeling was required to determine the extent to which water heaters could be modulated while still offering a consistent supply of hot water to the customer. Second, the monetary value of many of the aforementioned services depends on the transmission organization that monitors and controls the delivery of high-voltage electricity on the grid. These are the energy wholesalers, and can be Regional Transmission Organizations (RTOs) that cover large interstate areas, or Independent System Operators (ISOs) that cover smaller geographical areas. The economic value of the aforementioned services was obscured in the intricacies of the wholesale RTO and ISO markets.

A new report by the Brattle Group sheds light on the value that GIWHs can provide (Hledik, Chang, and Lueken 2016). Researchers found that the economic benefit of using water heaters for energy storage could approach roughly $200 per water heater per year, depending on the market, the control strategy used, and the type and capacity of the water heater. The markets that were analyzed were the PJM Interconnection (PJM), an RTO that serves parts of the Mid-Atlantic states, and the Midcontinent Independent System Operator (MISO), an RTO that serves the Midwest and parts of the Southern United States, as well as Manitoba, Canada. Specifically, researchers analyzed the 2014 PJM East market, the 2014 MISO market, and a future scenario for the MISO market[1]. A full graph of their results is show in Figure 1. Below is a summary of their results:

- Controlling water heaters for peak shaving is well suited to markets that are short on generation or transmission capacity, and that don't have volatile energy price fluctuations. In this context, peak shaving is similar to demand response – water heaters are curtailed 10-15 days per year, for 2-4 hours each time. This strategy offers relief for generation or transmission constrained areas by shedding load in times of high demand, but there is little incentive to perform arbitrage because the price of energy does not fluctuate greatly.

[1]The future scenario is based on the "Environmental" scenario in MISO's 2014 MISO Transmission Expansion Planning (MTEP) study. This scenario includes increased natural gas prices, significantly reduced coal powered electricity generation, and increased wind and natural gas generation capacity.

- Controlling water heaters for thermal storage is well suited to markets that have wide price fluctuations between peak and off-peak periods. In this context, thermal storage means charging the water heaters at night, and then curtailing them during the highest priced hours of the following day. The greater the size of the tank, the greater the number of hours the water heater can be curtailed without risking a hot water shortage to the customer. This strategy offers much greater value when controlling large capacity water heaters, and comes at little incremental cost compared to the peak shaving strategy.
- Controlling water heaters for frequency regulation has significant benefits in markets that have a need for grid balancing services. The benefits are tied directly to the market in which they participate, and fluctuate very little based on tank size. This strategy is not well suited to HPWHs. Additionally, the value of this service is not linear with supply; it will drop when there are an abundant number of resources on the grid to provide this service.
- Heat pump water heaters can also offer significant economic benefits by reducing the amount of energy consumed. Additionally, controlling HPWHs for peak shaving does not provide any benefit over an uncontrolled HPWH.
- Finally, the greatest benefit can be achieved from using a mix of these strategies in a portfolio based approach, rather than any one strategy in isolation. The greatest gain is also highly dependent on the market and location of these services.

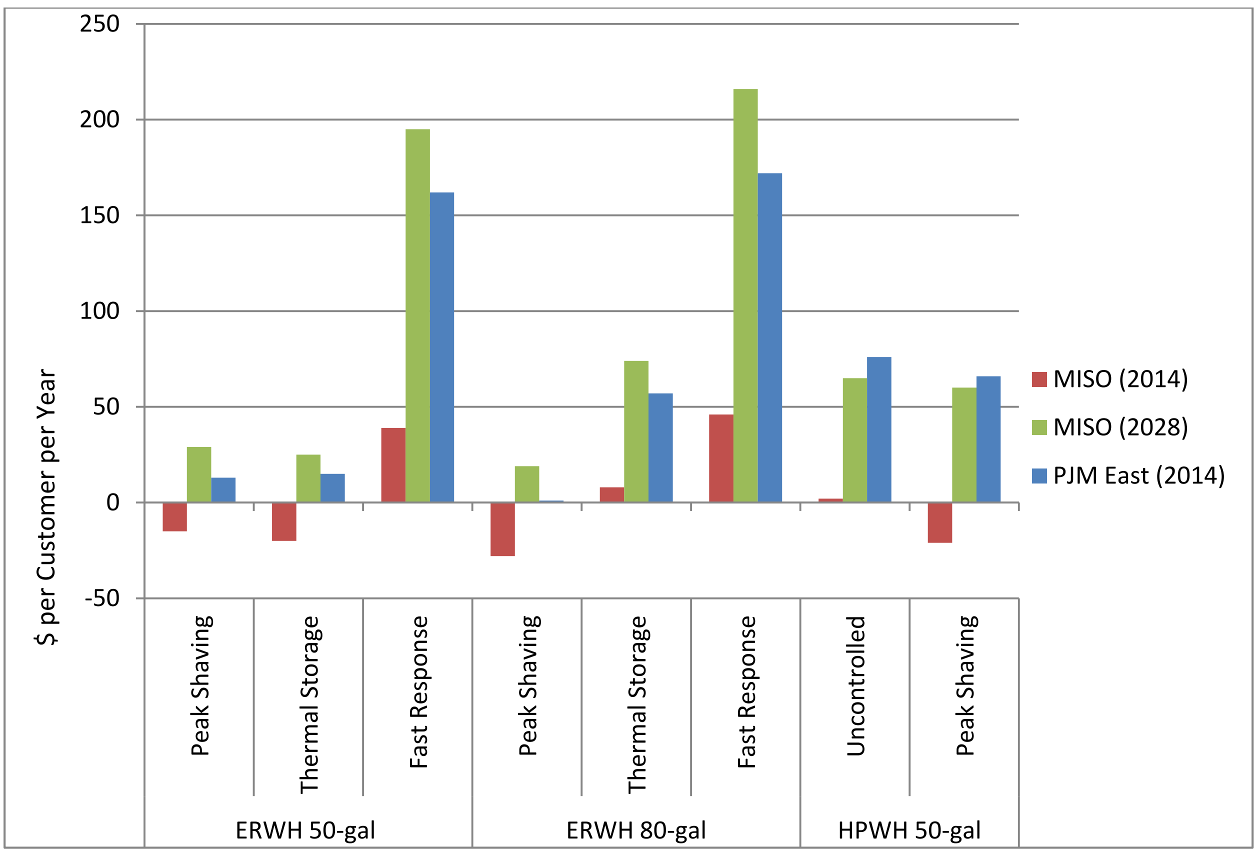

Figure 1. Economic benefit of controlling water heaters for peak shaving, thermal storage, and fast response energy storage. ERWH refers to an electric resistance water heater, HPWH refers to a heat pump water heater, and gal refers to the gallons of storage capacity. *Source:* (Hledik, Chang, and Lueken 2016).

Environmental Impacts of Water Heater Strategies

In the current generation mix of coal and gas for the PJM and MISO markets, researchers from the Brattle Group estimated that switching from a 50 gallon ERWH to a HPWH would cut emissions by roughly half. Additionally, switching from a 50 gallon ERWH to an 80 gallon ERWH used for thermal storage would increase emissions by roughly 10%. This is due to the greater standby losses associated with heating enough water in the tank for the full domestic hot water draw of the following day. In these markets there are no CO2 emissions savings from consuming energy during nighttime hours over daytime hours (Hledik, Chang, and Lueken 2016).

In the same scenario, but in a market with a greater penetration of renewables and with gas-fired generation replacing coal-fired generation[2], using an 80 gallon ERWH for energy storage would reduce emissions by roughly 30% compared to using an uncontrolled 50 gallon ERWH. The emissions reduction of replacing a 50 gallon ERWH with a HPWH would again result in roughly 50% emissions reduction (Hledik, Chang, and Lueken 2016).

Frequency regulation entails the fast increase and decrease of power to the water heater over a short duration of time, which effectively sums to zero net gain or loss of energy. Thus, providing ancillary services with water heaters shouldn't increase or decrease the energy consumption of the device by any significant degree. Because ancillary services are energy neutral, they're also emission neutral (Hledik, Chang, and Lueken 2016). However, the balancing service that frequency regulation provides enables the grid to support an increased penetration of renewables. There's no quantifiable analysis of this benefit that the author is aware of.

A Brief History of GIWHs

Great River Energy (GRE) is a generation and transmission company that serves Minnesota and parts of North Dakota. It has 28 member distribution cooperatives and more than 2,800 megawatts of generation. GRE has been controlling many of the water heaters of its cooperative members for load shifting for over 30 years, and has more than 110,000 water heaters under its control—about one-sixth of all its residential members.

GRE started controlling water heaters in the 1980s, when it developed a peak load reduction program. It controls members' electric resistance water heaters by turning them off during the day and turning them on and "charging" at night. In the mid 2000s, GRE became a member of MISO. By joining MISO, GRE could see the prices for energy for every hour of the following day. This opened up new options: GRE could participate in this price fluctuation in different ways, and it always had access to the cheapest power. In 2007 the state of Minnesota began mandating that renewable electricity be incorporated into the generation mix. This caused an influx of wind power on the grid, and due to excess electricity being generated during nighttime hours, prices during this time sometimes fell negative—meaning GRE could actually earn money from charging its customers' water heaters at night and consuming the excess energy production.

[2] Specifically, 70% natural gas-fired combined-cycle, 20% natural gas-fired combustion turbine, and 10% renewables

Currently, GRE has two water heater programs. The load shifting program—in which the water heaters are shut off during the day and allowed to turn on only at night—currently involves about 65,000 water heaters. This program is used primarily for arbitrage; it allows GRE to purchase the low-cost electricity from the MISO market during nighttime hours and avoid higher-priced daytime electric rates. GRE's other program is a peak-shaving program, which is very similar to a demand-response program. This program has roughly 45,000 customers enrolled, and the water heaters are allowed to charge whenever they need to. The water heaters are curtailed, at GRE's discretion, in 4- to 6-hour blocks, 20 to 30 times per year. The purpose of this program is to avoid peak-time pricing of electricity. As a secondary benefit, though, GRE's member distribution cooperatives save on demand charges incurred from GRE.

According to Gary Connett, director of member services at GRE, both of these programs have been a huge success. GRE is grateful that it started offering these programs so early, and that it has such a large load-shifting asset that most other utilities and generation and transmission companies don't have.

Additionally, customer satisfaction has been very high. Initially, customers were fearful of running out of hot water, but GRE has heard very few complaints. GRE found that customers in this program actually use less hot water. Customers appear more mindful of the hot water that they have and far more understanding of what they use it for. They also found that water heater control only worked well with single-family homes. Commercial buildings, hotels and motels, and multifamily residences were not successful with this program. These customers had much less-consistent hot water consumption patterns than single-family homes. And occupants in multifamily buildings—who didn't pay for their hot-water consumption—tended to use much more than occupants in single-family homes (G. Connett, Director of Member Services, GRE, pers. comm., February 12, 2015 and March 2, 2016).

Competing Technologies for New Installs

There are two new water heater controls on the market that are specifically designed for grid interaction and are able to provide frequency regulation. The first is made by Steffes Corporation and uses a well-insulated tank and an external control box. Steffes Corporation is currently working on integrating the control box into the water heater as a manufacturer installed OEM solution. Steffes Corporation's control algorithm can control water heaters as they are, without modification, or they can allow overheating of the water in the tank, essentially doubling the energy storage capacity, and then dilute the water back to standard domestic hot water (DHW) temperatures with a mixing valve before being delivered to the customer. In a field test by the Hawaiian Electric Company (HECO 2013), overheating the water in the tank didn't reduce the efficiency of the water heater due to the higher temperatures as would be expected. This is due to the water in the tank spending essentially the same amount of time at lower than normal temperatures as at higher than normal temperatures, making the efficiency change a wash (Podorson 2014).

The other control manufacturer is Sequentric and Battelle, which have developed an OEM control box that can be incorporated into a water heater in the factory to add grid interoperability. Sequentric's approach adds an additional utility controlled resistive heating element to the bottom of the water tank. A mixing valve isn't needed because temperatures never exceed that of standard domestic hot water. Because the water in the tank will naturally stratify, the utility will have control of the initially cold water at the bottom of the tank. The utility controlled resistive element is used to preheat this cold "make-up" water as needed to any temperature up to standard DHW temperatures. In this way, consistent DHW temperatures are maintained at the outlet. Additionally, if the grid controlled heating element fails or bidirectional control of the water heater is lost, the customer is simply left with a regular, functioning, electric water heater (Podorson 2014).

Competing Technologies for Retrofits

Two new controllers are available that attempt to add grid interactivity to the existing water heater install base. The first is manufactured by Power Over Time, and the second is manufactured by Sunnovations.

Power Over Time

Power Over Time markets themselves primarily as a software-as-a-service provider. They claim that the backbone of their product is their cloud infrastructure, and that their physical load controls can be used to control almost any load, including water heaters, pool pumps, agricultural products, and electric vehicles. Their products communicate over wireless broadband internet (WiFi) from the customer's home, with an option to use cellular service where WiFi isn't available.

Power Over Time has two controllers available for water heaters: one designed for indoor water heaters and one designed for outdoor loads, such as external water heaters or air conditioner compressors. The indoor product is installed in between the electrical panel and the water heater, and includes a solid state power relay, which enables the controller to ramp the power of the water heater up and down in 75W increments. Additionally, a temperature probe is installed on the hot water outlet pipe of the water heater, a few inches away from the outlet. The temperature probe is designed to detect "flow events"; it's not designed to determine the temperature or quantity of hot water leaving the tank. This system "infers" the temperature of the water in the tank from the hot water draw events and a measure of the electrical energy entering the tank. This was a deliberate choice on the part of the manufacturer to keep system costs down, allowing a small but acceptable loss of accuracy.

The outdoor retrofit solution is designed for customers that already have an external mechanical relay switch, such as those used by many utility demand response programs. Power Over Time's product is designed to directly replace the radio controller of those switches; the manufacturer claims that it is a five minute, $100 retrofit that converts a one-way radio frequency load control switch into a 2-way communicating switch (E. Lebow, CEO, Power Over Time, pers. comm., January 6, 2016).

Sunnovations

The Aquanta product from Sunnovations is installed in between the electrical panel and the water heater, and controls the water heater solely by opening the circuit; the product does not have the ability to incrementally ramp the power of the water heater up or down, or to force the water heater to turn on. It uses an enthalpy sensor installed inside the water tank to measure the temperature, i.e. the "charge level" of the water heater. The enthalpy sensor is installed by removing the pressure release valve, inserting the sensor, and then re-installing the pressure release valve. Installation doesn’t require any special equipment or training, and does not have to be performed by a certified plumber. The product communicates via the customer’s WiFi connection.

The Aquanta product is the only GIWH control that the author is aware of that has the ability to control some gas water heaters. Gas water heaters with electronic ignitions or with powered vents can be controlled by this product. The manufacturer estimates that they can control 40-60% of the gas water heaters currently in use in the United States, in addition to electric water heaters (M. Carlson, CEO, Sunnovations, pers. comm., December 17, 2015).

The Aquanta product saves energy by first learning the heating pattern of the home, and then by reducing and optimizing the set point temperature to match the anticipated load, reducing standby losses in times of low demand. The product is also demand response capable. At this time, the product is not intended for fast response storage such as frequency regulation or other ancillary services (M. Carlson, CEO, Sunnovations, pers. comm., December 17, 2015).

Recent Pilots and Programs

Hawaiian Electric Company (HECO) has been working with GIWHs for the past three years. They recently finished a pilot test of about 55 GIWHs that were used for frequency regulation; roughly half used Steffes technology and the other half used Sequentric and Battell technology. Both technologies showed positive results; they were able to track PJM’s fast regulation signal with greater than 90% accuracy – a score much higher than most generating plants. The results of the pilot haven’t been disclosed to the public, but HECO is in the process of installing another 499 GIWHs for another project; presumably because the first pilot was successful. Installation of the water heaters for this project is slated to be done by mid-summer 2016 (Y. Kawanami, HECO, pers. comm., February 5, 2016).

The PowerShift Atlantic project in the maritime region of Canada recently finished testing the aggregation of over 1,400 residential and commercial loads, including GIWHs, to provide ancillary services for the integration of wind energy. The region has some of the highest wind penetration in North America (9% of total load as of 2013), and the variability of their generation and load profiles are currently balanced by oil, gas, coal, and hydro generation resources. The project sent signals via radio or internet to participating buildings to turn select electrical appliances on or off, creating virtual power plants (VPP). These VPPs provided the equivalent of 10 minute spinning reserves, to balance demand against the variability of wind generation (Beauvais and Losier 2013).

The PowerShift Atlantic project successfully demonstrated the technical feasibility of this solution, but the final report has not yet been disclosed to the public. On the residential side, it was demonstrated that broadband internet offered a faster and more reliable connection than the use of radio frequency advanced metering infrastructure (AMI). Residential customers were generally (80%) satisfied with the program experience (Beauvais and Losier 2013; Natural Resources Canada 2015).

For the retrofit products, the Gas Technology Institute has begun a field test of the Sunnovation’s Aquanta product in Minnesota. The field test is being supported by Xcel Energy and Centerpoint Energy, and began in January of 2016. The test will include 50 Aquanta units, installed on both electric and gas water heaters, and aims to determine the energy efficiency and load shifting potential. According to the manufacturer, field trials with 12 other utilities or distribution partners are primed to begin in 2016 (M. Carlson, CEO, Sunnovations, pers. comm., December 17, 2015).

The Power Over Time product has been piloted by Connexus Energy. The pilot ran from June 2015 to January 2016, and included nine indoor controllers and two outdoor controllers, as well as ten electric vehicle controls. According to the manufacturer, WiFi communication was extremely reliable and peak shaving was accomplished without snapback - the additional consumption of energy after the peak shaving event. Additionally, another pilot is expected to begin with East River Energy, a generation and transmission company in South Dakota in 2016 (E. Lebow, CEO, Power Over Time, pers. comm., January 6, 2016).

The Sacramento Municipal Utility District (SMUD) is testing smaller, 20 gallon grid interactive pre-heaters as an add-on to customer's existing gas or electric water heater. The utility operates the pre-heater for behind-the-meter energy storage (Hledik, Chang, and Lueken 2016).

Conclusion

The potential of this technology for use in utility demand-side management programs is vast. In 2009 there were at least 44 million electric storage water heaters in the united states, representing 39% of all the water heaters in the country[3] (EIA 2009). At roughly 2 kW of frequency regulation per water heater (Podorson 2014), and consuming roughly 120 TWh of energy (EIA 2009)[4], the potential for this technology to provide energy efficiency and grid balancing is grand.

Furthermore, as more renewable sources of energy are put on the grid, the need for regulation will only increase, and the environmental impact of electric water heaters will decrease. This trend has already started. Between 2005 and 2014, carbon emissions per mega-watt-hour declined by about 16%. The Environmental Protection Agency (EPA) estimates that coal-based generation will decline 20–22 percent in 2020 and 25–27 percent in 2030. Renewable energy resources currently make up over 30% of the nation's generating fuel mix, and will only increase as time goes on (Dennis 2015).

Results of pilot projects are preliminary but promising. The successful demonstration of GIWHs with integrated grid controls was shown twice in 2015, first with the PowerShift Atlantic project and second with the HECO demonstration project. GIWHs were shown to provide frequency regulation very well, but the full results of the studies have yet to be disclosed. Pending these results, the outlook for this technology looks promising.

The more recently introduced retrofit products are yet to be thoroughly vetted. Only one pilot has been completed; the Connexus Energy pilot of the Power Over Time product. This pilot didn't attempt to measure energy savings; instead, researchers found that communication over WiFi was reliable, and that peak energy savings did occur without snapback (the increased usage of water heater energy after a curtailment event). Numerous pilots are slated for 2016, which will help clarify the full value that these retrofit products can bring to the grid.

[3] Calculated by subtracting the number of tankless water heaters from the number of electric water heaters.

[4] Assuming tankless water heaters used, on average, the same amount of energy as other electric water heaters

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