Evaluating Peak Load Shifting Abilities and Regulation Service Potential of a Grid Connected Residential Water Heater

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ABSTRACT

Load profile for an electric utility or a system operator very rarely resembles a flat line. With increased penetration of renewable energy sources, generation is not constant either. Regulation service provides the resources an RTO/ISO (Regional Transmission Organizations / Independent System Operators) or a utility needs to maintain a continuous balance between generation and load.

Storage type electric water heaters typically use power when there is hot water drawn from the storage tank. This hot water draw coincides with the peak load on the electricity grid – early morning between 7 am – 9 am when people leave homes and in between 6 pm and 9pm. There is tremendous value in shifting this electric water heater load to off-peak times. In off-peak mode, water is heated during 11pm – 6am when the load on the grid is low and there is need for regulation service.

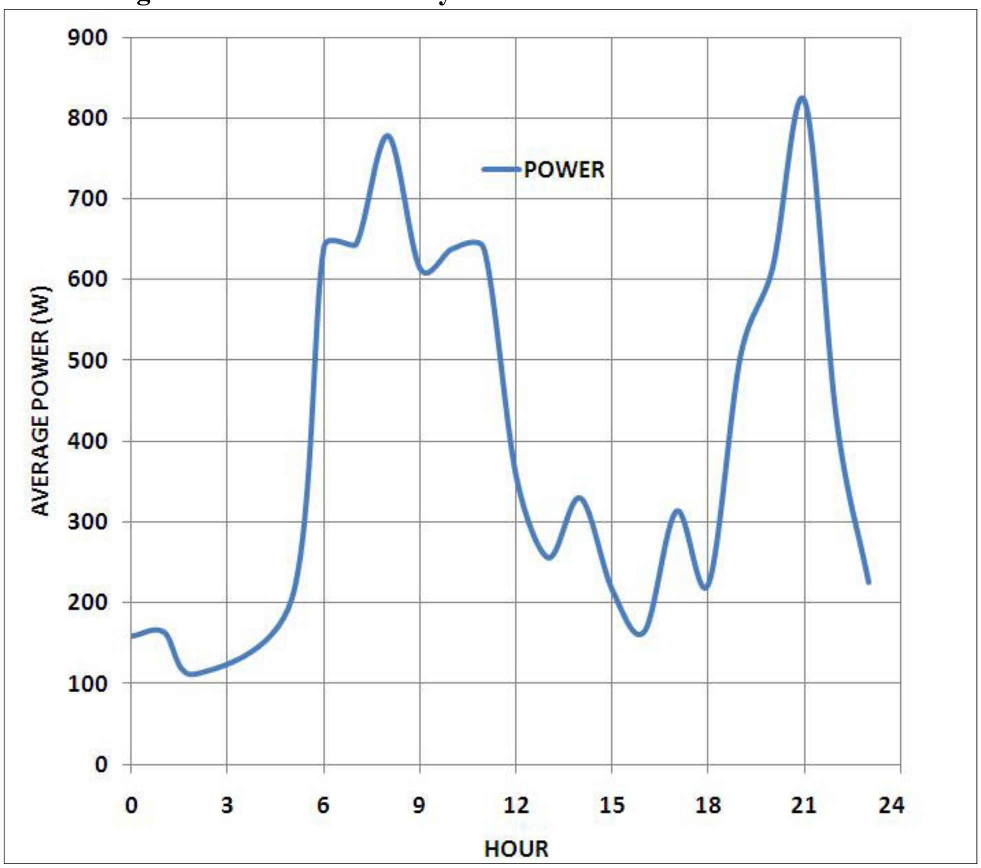
This paper describes the technology used within a tested water heater and its control system and documents the results from series of tests performed to understand peak load shifting and regulation service capabilities. The energy storage capabilities are extended by setting thermostat at a higher temperature (170°F) and using an external mixing valve to reduce water temperature for end use devices. The water heater is configured to receive signals from a RTO/ISO and provide regulation service. The results from a control scheme where the water heater is getting regulate 'UP' or 'DOWN' (i.e. increase or decrease power draw) signals from an energy aggregator are presented. A baseline water heater case is also presented to help users understand the pros and cons of such a water heater.

Introduction

Water heating energy use is second only to space conditioning energy use as the highest energy load in residential buildings. In U.S. residential market the primary means of heating water is storage type gas water heater, electric resistance water heaters and more recently heat pump water heaters and instantaneous gas water heater. Water heating is also a significant load in some commercial and institutional buildings like food service establishments and dormitories. In 2010, 0.53 quadrillion BTU's (British Thermal Units) of electricity was used for water heating in U.S. residential and commercial buildings. Electric resistance heating coupled with an appropriately sized storage tank is the primary means of heating water with electricity. Typical water heaters have one or more heating elements with an individual thermostat for each heating element. As cold water enters the water heater, the resistance elements heat the water until the thermostat is satisfied. This hot water is stored in the tank until there is a demand. As the hot water is drawn from the water heater, cold water enters the water heater and the cycle repeats. This ON-OFF cycling of the resistance heaters generally tracks the water draw profile from the water heater.

From an electric utility perspective the electric water heater is a resistive load on the grid that starts drawing power as soon as there is water draw from the storage tank. This power draw coincides with the peak load on the electricity grid. Water draw goes up early in morning and has another peak later in the day. Figure 1 shows the hourly average power draw from four field-installed resistance water heaters from EPRI's Energy Efficiency Demonstration project. The data is for first week of October 2011. The power draw shows two peaks, one early in the morning and one late evening which coincide with the peak load on the grid. Modifications to the load profile of electric water heaters can help utilities and grid operators to maintain a better balance between generation and load.

Figure 1. Average Power Draw for 7 Days of 4 Field Installed Resistance Water Heaters



Effect of Renewables on the Electric Grid

Renewable Portfolio Standards (RPS) from numerous states requires utilities to have a larger percentage of their energy generated from renewable resources. The RPS is a regulation that requires increased generation from renewable energy sources such as solar, wind, geothermal etc. These renewable resources, especially wind and solar have a varying power output throughout the day. Solar PV (photovoltaic) has its peak output in between mid-morning and mid-afternoon while wind energy is usually abundant at night. The output further varies by other climatic conditions such as cloud cover. Integrating these renewable sources with varying output is a challenge for grid operators. At the end of 2010 the United States had more than

40,000 MW of land-based installed wind power capacity. The interest in wind energy remains high and capacity addition through 2013 is predicted to be in excess of 15,000 MW.

Balancing generation and load in real time is difficult because of non-coincident fluctuations in both. With wind generation fluctuating, other generating assets have to adjust not only to the load but also to the variations in wind power. Wind generation in the U.S. is higher during off-peak hours than during peak hours. During off-peak hours base load generators are running at their minimum possible power output. Additional wind generation during this period is either curtailed or is unusable due to lack of loads to consume this free resource.

Energy Storage and Load Control with Electric Water Heater

The increased deployment of renewable generation, high cost of energy during peak demand and the ability to buy and sell electricity related products and services has created interest in energy storage systems. Energy storage systems are used to provide a buffer in between the time when the energy is generated and the time when the energy is utilized. Energy storage is fairly simple in some energy sources like natural gas, where the gas can be compressed and stored for future use. In electric energy though, storage avenues are limited and generally expensive.

High penetration of electric storage-type water heaters in the U.S. residential market and ease of control makes electric water heaters an attractive end use device for load control. A number of utilities already have load control programs incorporating electric storage-type water heaters. The availability of low cost control devices, increased connectivity and emergence of energy markets has further opened avenues for peak load shifting with electric resistance water heaters. A storage-type electric resistance water heater can now communicate with a remote server which can decide on when to charge the water heater and at what rate. Various control strategies can be implemented keeping in mind the customers' needs as well as the electric grid's requirement.

Usually in a storage water heater, the term 'storage' is used more in the sense of water storage (i.e. tank size) than energy storage. The storage-type water heater can be envisioned as a battery that can store energy and be charged in an effective way. A standard 50 gallon water heater with a thermostat set at 125°F can store about of 8 kWh of energy. Assuming an average storage size of 50 gallons and thermostat set at 125°F and cold water temperature of 60°F the 53 million households that have electric storage water heaters have an aggregated storage capacity of 400 GWh – equivalent of running a 1000 MW power plant for 167 days. This is a tremendous resource and has potential to contribute in the energy storage arena.

Smart Electric Water Heater

A Smart Electric Water Heater developed by Steffes Corporation is tested at EPRI's Knoxville lab. This product consists of a Rheem Marathon water heater coupled with Steffes Corporation's proprietary control box. A netbook computer provided by Steffes Corporation is used for communication between the controller and the server through an internet connection. The Steffes server communicates with the server controlled by the RTO/ISO. Once particular signals are received by the Steffes server, the server relays the signal down to the individual water heaters depending upon the level of charge each water heater has.

The storage tank is an 85 Gallon water tank with two separate resistance heating elements. The electric resistance elements are rated at 4500W each at 240V. The power source in the lab is single phase 208 volts with a 20A breaker. With the reduced voltage the wattage of each element is reduced to 3000 W.

Figure 2. Smart Electric Water Heater from Steffes Corporation

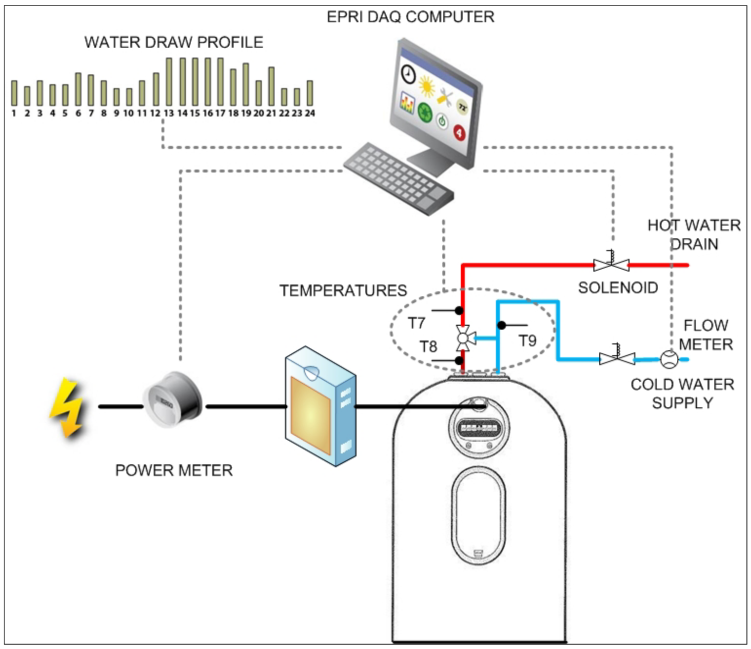
The water tank has six thermocouples inserted at various depths to record temperature distribution within the tank. Based on the temperature readings from the thermocouples, the control program installed on the netbook determines the current charge. This value and the temperatures are constantly communicated to the Steffes server. Depending upon the control strategy chosen, the server directs the control program to turn the heaters ON and OFF. The actual turning ON and OFF of the heater elements is done in the control box. A power meter is also included in the control box to determine the instantaneous power dissipated by the heater elements. In the current setup, the upper thermostat is set at 170°F and the lower thermostat is set at 155°F. The higher water temperature allows the smart electric water heater to store more energy. 170°F water coming out of the water heater is too hot for any domestic hot water application. To temper the water down to more usable range a mixing valve is installed in between the hot water and the cold water pipe. This valve is set at the actual temperature a user expects the hot water to be delivered to the terminal use devices. In this test setup the temperature is set at 123°F for the mixing valve. This is the temperature one would otherwise set the thermostat at on a normal water heater.

A separate EPRI data acquisition computer with its own instrumentation is installed and connected. This computer monitors the water inlet temperature, hot water temperature and the mixed temperature of water after the mixing valve. This EPRI computer also has the ability to simulate water draw from the water heater according to a predefined hourly profile by controlling a solenoid valve. A separate power meter is installed to measure instantaneous power and total energy delivered to the water heater. A water flow meter is installed on the cold water line to measure water flow. A schematic of the EPRI instrumentation and test setup is shown in Figure 3.

Test Plan

The test plan consists of running the smart electric water heater in two control strategies – a baseline strategy where the water heater acts as a regular domestic water heater and a regulation service strategy where the advance capabilities of communication and power modulation are investigated.

Figure 3. Schematic of EPRI Installed Instrumentation and Data Acquisition



A fixed water draw profile that is controlled by the EPRI data acquisition computer is imposed on each of the above strategies. Figure 4~~Figure 4~~ shows the water draw profile that was used as a standard water draw profile. This water draw profile is chosen from ASHRAE 2011 HVAC Applications handbook which shows average hourly hot water use patterns for all families. The overall average daily water draw in this case is 67 gallons. This same profile is repeated every 24 hours for 5 days for each of the strategies evaluated. Data is recorded every 10 seconds

Baseline Water Heater Strategy

A regular water heater strategy is implemented to understand the behavior of the water heater as a baseline case. The water draw profile from Figure 4~~Figure 4~~ is imposed with the help of EPRI data acquisition computer. The thermostats in this strategy are set to 125°F and no external control is implemented to control the water heater elements. shows the actual water draw profile and the hot water temperature. The hot water temperature is measured at the outlet of the water heater before the mixing valve. The temperature is slightly less than 125°F because of small error in the thermostat setting.

The power draw and energy corresponding to the water draw in is Figure 5 shown in Figure 6. The figure shows that the power draw follows the water draw closely. As soon as there is water draw from the water heater the heating elements turn ON and re-charge the heater. This situation is shown in Figure 6. The only time when the resistance heaters are not using power is at 3:00 am where the water draw is very small. It is also evident from the Figure 6 that the power draw is always 3 kW which is the rated power for the heating elements at 208V.

Figure 4. Water Draw Profile Imposed on the Water Heater for Testing

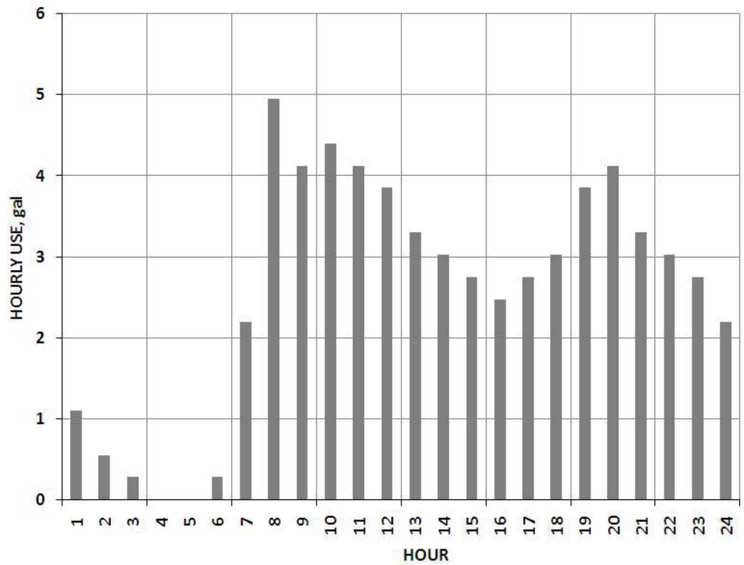
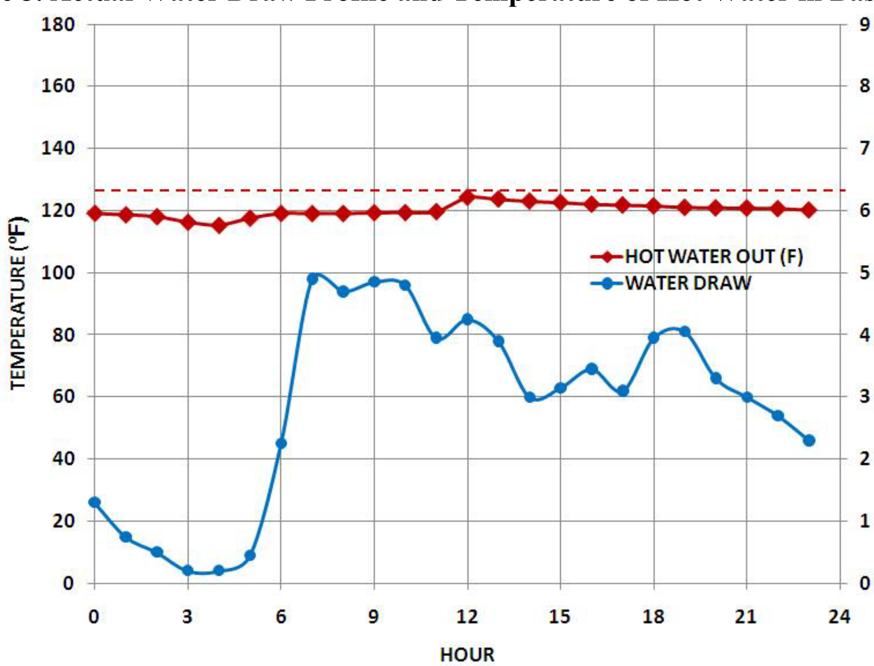
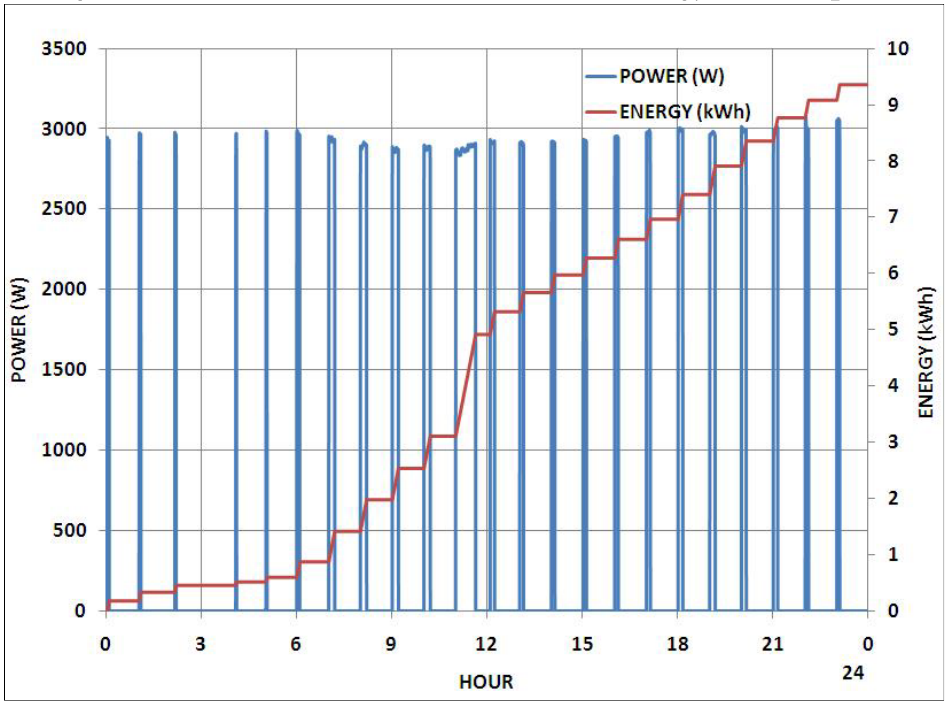


Figure 5. Actual Water Draw Profile and Temperature of Hot Water in Baseline Case



The energy consumed during the 24 hours is 9.36 kWh which is an average power draw of 0.39 kW for the whole day. This is significantly different than the 3 kW power draw that the utility sees for short durations. The problem is further exacerbated when thousands of such water heaters come on during peak load period for the utility. Yearly energy consumption with this profile will be 3417 kWh and at wholesale energy prices would cost \$ 175 to operate per year. In the operating cost calculation the water draw profile and the DA-LMP (day ahead locational marginal pricing) curve is assumed constant for the whole year.

Figure 6. Baseline Case Power Draw and Energy Consumption



Regulation Strategy using an Electric Water Heater

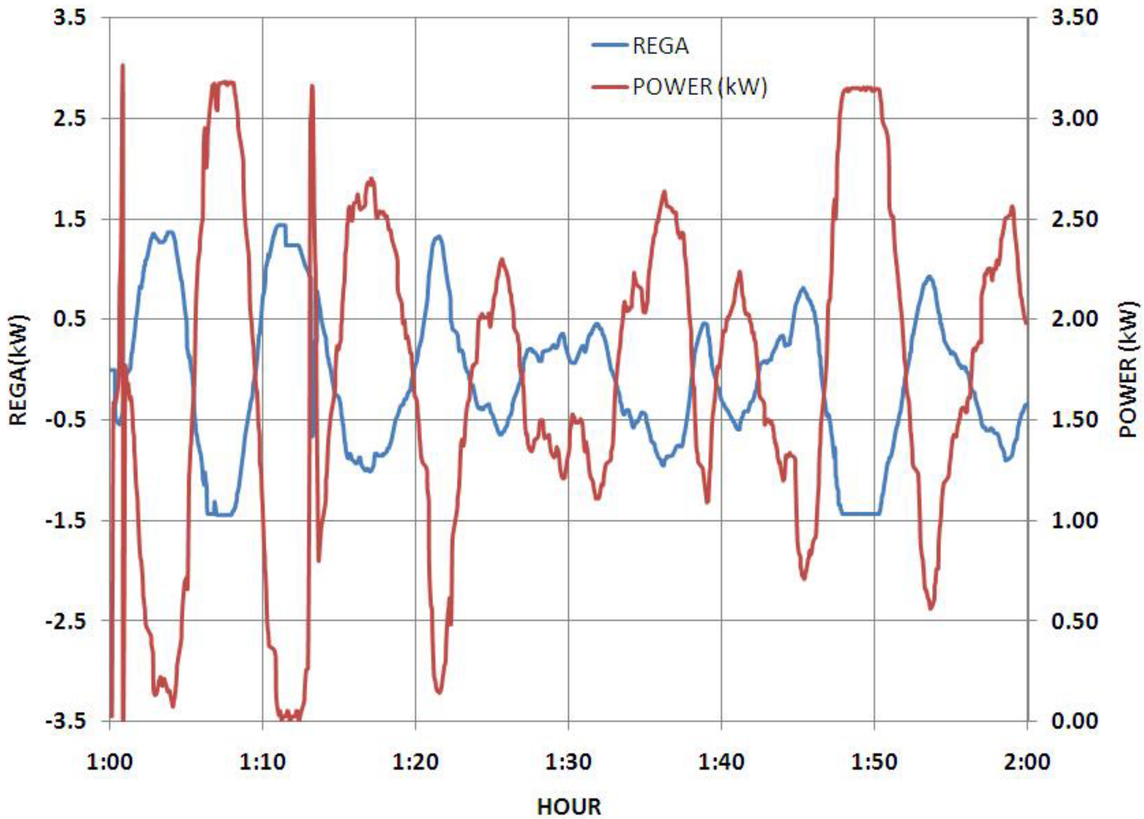
Regulation service is a part of ancillary services which supports the stable and reliable operation of the electric system. Regulation service provides the resources an ISO/RTO needs to maintain a continuous balance between generation and load. Loads change in real time and wind generation fluctuates with wind speed. This varying wind power and changing load results in variations in frequency which is kept at a nominal 60 Hz in the U.S. Excessive load on the system causes frequency depression and vice-versa. The sudden addition of renewable power, without a corresponding increase in load and/or a decrease in conventional generation results in an increase in frequency. Likewise if renewable power falls off rapidly the frequency reduces. To maintain this frequency at 60 Hz, adjustment is needed in terms of either generation or load. These adjustments are called frequency regulation.

Regulation services are further classified on the basis of how quickly resources can respond. For example, in PJM (an RTO serving 13 states and District of Columbia in the eastern interconnection) region regulation is a 5 minute service and is defined as the ramp rate in MW/min. Resources such as generators can provide regulation service but are limited by the ramp rates. For example, large power plants with a ramp rate of 1MW/min can only offer 5MW of regulation capacity in the 5 minute time frame. A demand side regulation resource, like aggregated water heaters, can ramp up or down at a higher rate typically in the range of 10MW/min. The value provided by these fast responding sources is much higher than the slower responding sources. A faster response leads to more accurate response to signals from RTO /ISO (Automatic Generation Control AGC or Area Control Error ACE correction signal) and avoids hunting (overshooting and undershooting) of the ACE correction needs.

A regulation strategy can be implemented in a smart electric water heater to provide frequency regulation in the energy marketplace. The same water draw profile shown in Figure

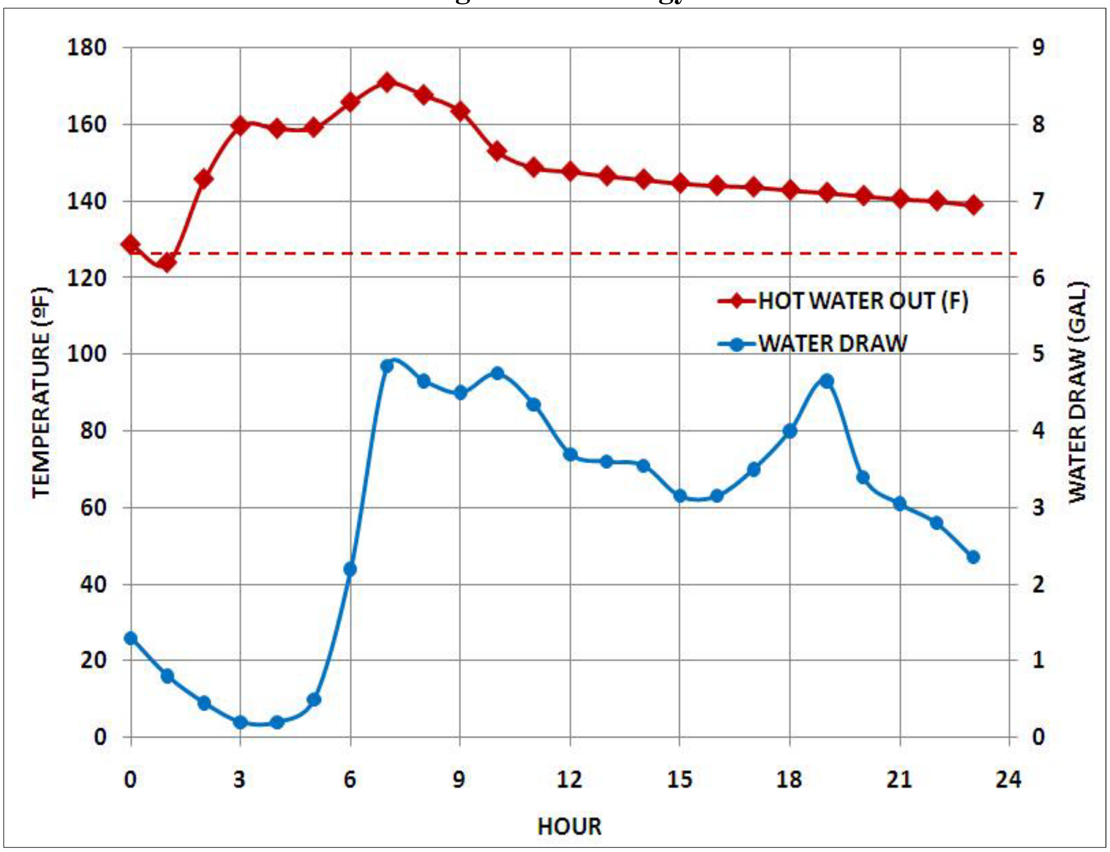
4~~Figure 4~~ is imposed on the smart electric water heater which is setup to implement the regulation strategy. In regulation strategy the water heater is limited to run during low LMP hours (11:00 pm to 7:00 am). The thermostats in this case are set at 170°F (upper) and 155°F (lower). For this strategy to work the netbook connected to the smart electric water heater has two way communication with a server hosted by Steffes Corporation which acts as an aggregator. The Steffes Corporation server is connected to multiple such units and aggregates the load and communicates information gathered to another server setup at PJM. There is a continuous high speed exchange of information between these various devices to make this strategy work.

Figure 7. REGA Signal and Power Dissipated While Running Regulation Strategy



The Steffes server continuously communicates with the smart electric water heaters that form its fleet. The charge value of each connected water heater is monitored and aggregated. The Steffes server communicates a TREG (Total Regulation) value to PJM (RTO) terms of a single MW value. For e.g. if the smart electric water heater has a heating element rated at 3 kW and there are 1000 such smart electric water heaters in one fleet then the TREG will be 1.5 MW. This is because the heater elements need to start at baseline of 1.5 kW (one half of 3kW) to provide 1.5 kW UP regulation and 1.5 kW DOWN regulation. Real time support of TREG is critical for PJM to determine the amount of regulation PJM requires of a particular fleet. REGA (Fleet Regulation Signal in MW) is generated by PJM which is bound by +TREG / -TREG. This is the signal that PJM sends to the fleet operator to regulate UP or DOWN. Once the REGA signal is received by the Steffes server it breaks down the total regulation required into smaller parts and commands all connected smart electric water heaters to act accordingly. The Steffes server can selectively decide all or some of the smart electric water heaters connected provide regulation depending on their charge level. This communication between the smart electric water heater, Steffes server and PJM is taking place every 2 seconds. Figure 7 shows the REGA values and power dissipated during one hour of operation between 1 am and 2 am. The REGA signal and the power dissipated are complimentary due to fact that smart electric water heater is a demand side resource. When the REGA signal goes negative it means increase consumption and when REGA is positive it means decrease consumption.

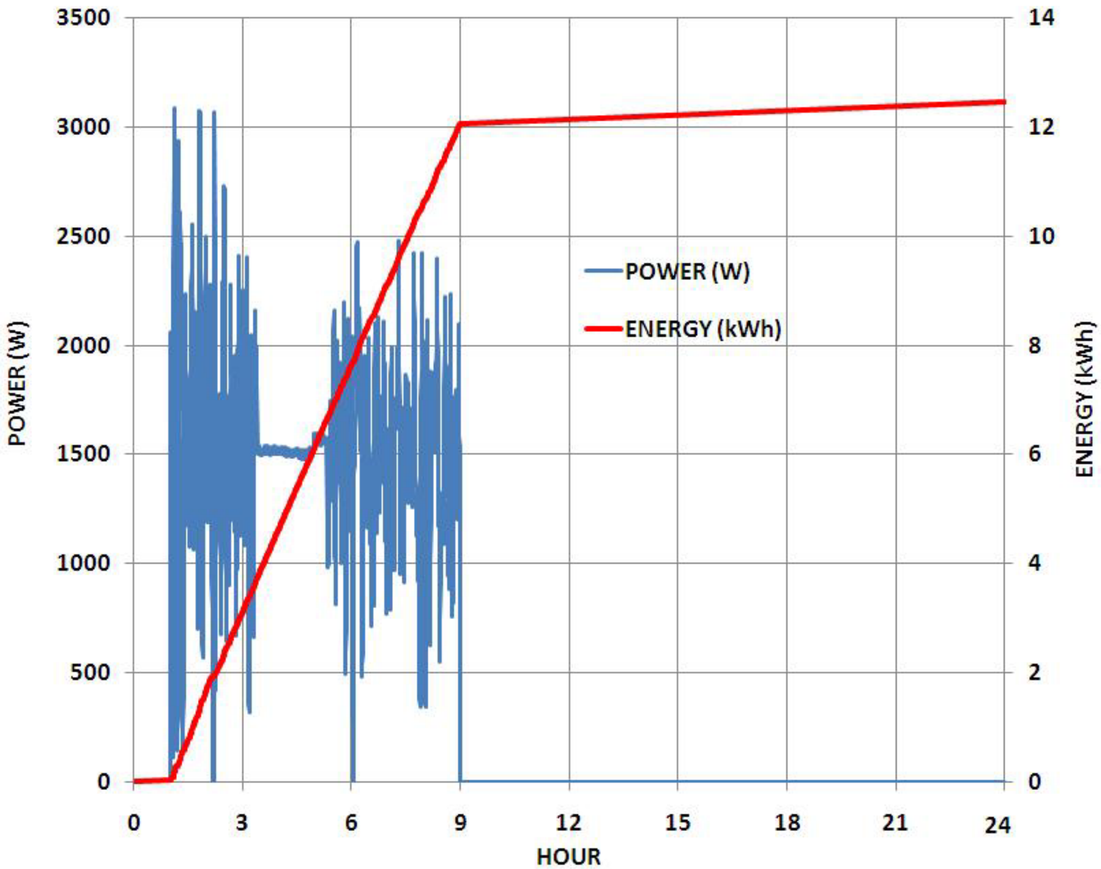
Figure 8. Water Draw Profile and Temperature of Hot Water While Running Regulation Strategy



The water draw profile and hot water temperature while running the regulation strategy is shown in Figure 8. The hot water temperature is consistently above 125ºF (except for at 1 am) while running this strategy. Although the water temperature reaches much higher values, a mixing valve tempers the water down to a more suitable 123 ºF. The overall power draw and energy consumption is shown in Figure 9. The total energy consumption in the regulation strategy is 12.47 kWh. Total cost to operate the water heater for this day is $0.40 or a yearly operating cost of $145.9.

RMCP or Regulation Market Clearing Price is price in $/MWh of regulation provided. This payment is made to the fleet operator in lieu of the regulation service provided by the smart electric water heater. The payment made to a fleet operator is for the regulation capacity offered into the market (and cleared in advance by PJM) and not the actual regulation provided. The regulation value provided by the smart electric water heater can be calculated from the data acquired. During the 8 hours of operation, 12 kWh of regulation was provided by one smart electric water heater. Integrating the regulation capacity offered and the RMCP yields a financial benefit of $0.185 /day/smart electric water heater.

Figure 9. Regulation Case Power Draw and Energy Consumption



Summary of Test Results

Table 1 shows the operating cost per year for a regular water heater and a smart electric water heater. The regular water heater is always running without any control on the resistance heaters i.e. no control besides the built-in thermostat is used. This is similar to a storage type electric water heater installed in a typical home. The savings generated while using the regulation strategy are twofold; first the water heater consumes energy only when energy prices are low and second the water heater provides a valuable regulation service which results in a payout. In both cases, the water temperature is held to the set point and the end user is not inconvenienced.

Table 1. Comparison of Wholesale Energy Cost Per Year

Type of Water Heater	Wholesale Energy Cost ($/Year)
Uncontrolled (Baseline) water heater	175
Smart Electric Water Heater with Regulation Strategy	145.9 (- $ 67.5 Payout for regulation service)

Conclusions

A smart electric water heater was tested in EPRI's Thermal Environmental Laboratory in Knoxville, TN. The smart electric water heater is compared with a regular water heater to demonstrate the regulation capabilities of such a device. The peak load shifting ability is verified by comparing operating cost of a smart electric water heater to operating cost of a regular water heater under identical conditions, where the wholesale price of electricity is assumed to be a reasonable proxy for load on the grid.

Electric utilities can deploy smart electric water heaters in their service territory and implement various control strategies to control water heater load and provide regulation services depending on the wholesale markets they operate in. By aggregating water heaters (or other suitable end use devices) the electric utility industry can shift some portion of the regulation requirements to load side from the generation side. A recent boost to this technology is from FERC order number 755 (18CFR Part 35, October 20, 2011) 'Frequency Regulation Compensation in Organized Wholesale Power Markets'. The order requires RTO's and ISO's to pay regulation rates depending upon the resources ability to follow the dispatch signal. This order underscores application of this technology for use in electric system reliability (providing regulation service).

The same smart electric water heater can be run in various other control strategies like optimizing LMP (Locational Marginal Pricing), following control signal from other utilities (for e.g.: Bonneville Power Administration) and optimized strategies to fit particular applications.

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