Peak Load Shifting by Thermal Energy Storage

Assessment of a Smart Electric Water Heater

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Technical Update, December 2011

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THE FOLLOWING ORGANIZATION PREPARED THIS REPORT:

Electric Power Research Institute (EPRI)

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

ACKNOWLEDGMENTS

The following organization prepared this report:

Electric Power Research Institute (EPRI)
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H. Upadhye
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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Peak Load Shifting by Thermal Energy Storage: Assessment of Smart Electric Water Heater. EPRI, Palo Alto, CA: 2011. 1021965.

ABSTRACT

Load profile for a utility or a system operator consists of peaks and valleys and very rarely resembles a flat line. Reducing the load that contributes to peaks and shifting it into the valleys is an important strategy in flattening out the load profile. One way to modify load profile is by controlling end-use devices such as electric water heaters and air conditioners to shift peak load to off-peak hours, thus achieving a better balance between the supply and demand of electricity.

A growing part of this balancing act is the increasing use of renewable energy generated by sources such as wind and solar-driven technology, which are by nature unpredictable. Sometimes the renewable energy is available when it is not needed, and vice versa. These types of resources ramp up or down very quickly depending on the weather—a wind gust will rapidly increase the output from a wind farm, or cloud cover will suddenly decrease output from a photovoltaic installation. Integrating these renewables into the electricity grid is a major challenge for the grid operator.

A conventional storage-type electric water heater uses power when hot water is drawn from the storage tank. This typically coincides with times of peak load on the electric grid—in the morning between 7 and 9 a.m. and in the evening between 6 and 9 p.m. There is tremendous value in shifting this electric water heater load to off-peak times. In off-peak mode, water is heated when the load on the grid is low.

This update describes the technology used within a smart electric water heater and its control system and documents the results from series of tests performed to understand the energy storage and peak load shifting capabilities. Such a water heater can also be used to provide regulation service when configured to receive signals from a regional transmission operator (RTO) or independent system operator (ISO). Various control strategies can be implemented, depending on the signal received from the RTO/ISO. Three such control strategies were tested in the lab, as described in the report. A baseline water heater case is also presented to help users understand the pros and cons of such a water heater.

PRODUCT DESCRIPTION

This technical update from the Electric Power Research Institute (EPRI) reviews the technology of storing energy in hot water and explores the potential for implementing this form of thermal energy storage—through means of smart electric water heaters—as a way to shift peak load on the electric grid. The report presents conceptual background, discusses strategies for peak load shifting and demand response, documents a series of laboratory tests conducted on a representative model of smart water heater, and explores possible scenarios for operation and control.

Background

A conventional electric water heater starts heating stored water as soon as water is drawn from the heater. This water draw typically coincides with times of peak load on the electric grid—in the morning between 7 and 9 a.m. and in the evening between 6 and 9 p.m. A smart electric water heater, in contrast, heats water during off-peak hours, when the price of electricity is lower, effectively using thermal energy storage as a means of load shifting. With load profile constantly changing as millions of devices turn on and off, and with renewable energy sources such as wind and solar being by nature unpredictable, grid operators are greatly interested in using energy storage as a way to balance supply and demand of electricity. Storage-type electric water heaters represent one of the most cost-effective and readily available potential storage options, especially in the U.S. residential market. In essence, the installed base of electric water heaters in the United States represents a thermal "battery" of major proportions. The concept of the smart electric water heater has been introduced as a way to tap into this thermal battery. The term *smart electric water heater* can be defined as an electric storage-type water heater with controls to modulate power, instrumentation to determine the charge level, and real-time two-way communication capabilities with a remote server.

Objectives

- To evaluate the thermal energy storage and peak load shifting/demand response abilities of a smart electric water heater
- To investigate the ability of the smart electric water heater to communicate with a remote server and follow signals from a system operator

Approach

A representative smart electric water heater was tested at EPRI's Thermal Environmental Lab in Knoxville, Tennessee, by subjecting the water heater to a fixed water draw profile. Performance of the smart electric water heater was evaluated for peak load shifting and savings in operating costs as compared to a regular electric water heater. The project team also investigated various control strategies for the smart electric water heater.

Results

Test results confirmed that the smart electric water heater is capable of following signals from a remote server to enable shifting of peak load to off-peak hours. An operating cost comparison provided in the report shows the savings generated by using various strategies. Multiple smart electric water heaters could be aggregated to participate in the electricity markets and provide economic benefit.

Applications, Value, and Use

For utilities considering the potential of smart water heaters as a strategic approach to load shifting, possible applications include the following:

- Incorporating smart electric water heater technology into existing or new demand response programs
- Leveraging smart electric water heaters as a means to integrate renewable energy
- Aggregating smart electric water heaters, configured to receive signals from a regional transmission operator or independent system operator, to provide ancillary services such as regulation

Keywords

Demand response
Thermal energy storage
Smart electric water heater
Peak load shifting
Ancillary services
Control strategies

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EXECUTIVE SUMMARY

Introduction

This technical update reviews the technology of storing energy in hot water as a means of thermal energy storage. The utility industry has long been interested in energy storage options. Storing energy in storage-type electric resistance water heaters is one of the most cost effective and readily available options, especially in the US residential market. In 2010, 0.53 quadrillion BTU's of electricity was used for water heating in residential and commercial buildings. Residential water heating with electricity alone was 0.44 quadrillion BTU's. In 2007 there were roughly 53 million households (42% of all residential buildings) in the US with an electric water heater [17]. Assuming an average size of 50 gallons and hot water temperature set at 125ºF, the installed base of storage-type electric water heaters corresponds to a thermal battery of 400 GWh.

A concept of 'Smart Electric Water Heater' is introduced as a way to tap into this huge thermal battery of 400 GWh. A smart electric water heater is defined as an electric storage-type water heater with controls to modulate power, instrumentation to determine the charge level and real time two-way communication capabilities with a remote server.

Smart Electric Water Heater Evaluation

A smart electric water heater developed by Steffes Corporation of Dickinson, ND is evaluated as part of laboratory tests. This smart electric water heater is subjected to a battery of tests which consists of drawing hot water on a fixed schedule while charging (adding heat) the water heater according to different control strategies. With the advent of wholesale energy markets and the accessibility to the real time and day ahead market data a strategy based on various market parameters like Locational Marginal Pricing (LMP) can be developed. Three such strategies are explained and evaluated in laboratory tests:

- Optimizing Locational Marginal Pricing – In this operating strategy the smart electric water heater draws power when the LMP's are lower than the 14 day running average of LMP at a given time. The smart electric water heater also draws power when the water heater is low on charge to avoid end-user complaints.
- Regulation Strategy – This strategy is used to provide a regulation service while running the optimizing LMP strategy. In this strategy the smart electric water heater follows a regulation signal from a remote server to provide frequency regulation.
- 'Balancing Reserves Deployed' (BRD) following strategy – In this strategy BRD signal is received from Bonneville Power Administration and the power draw is modulated accordingly.

Other advanced strategies can be built around the smart electric water heater utilizing its control and communications capabilities.

The peak load shifting ability of this smart electric water heater is approximated by qualifying the economic benefit gained by using such a water heater over a regular water heater. Since the exact load on the grid at any given instant is not readily available, price of electricity can be considered as a reasonable proxy for the load. An optimization strategy to reduce the operating cost will require the smart electric water heater to charge when the load on the grid is low. This effect in essence is peak load shifting.

The test results show that the operating cost of a smart electric water heater is 21.5% lower than that of a regular water heater when using the ‘Optimizing LMP’ strategy. With regulation strategy further economic benefit can be gained from providing an ancillary service to the market. Test results for regulation strategy showed operating cost difference of 18% due to lower LMP at time of use. A further benefit of 46% was gained by using smart electric water heater as a regulation service provider. In Balancing Reserves Deployed strategy the economic benefit was not studied.

Table 1-1
Smart Electric Water Heater Operating Cost Summary (Based on Wholesale Prices)

Type of Water Heater	**Energy Cost ($/Year)**		
	Uncontrolled	**Optimizing LMP**	**Regulation**
Regular Water Heater (Uncontrolled)*	111.40	100	175
Smart Electric Water Heater		78.50	145.9

*The cost of operation of regular water heater is different for different strategies due to different days that were used in calculations and different sources of data (MISO/PJM). Please refer to appendix for calculations.

Opportunities and Challenges for Utilities

A smart electric water heater is a low cost end use device for utilities looking to implement peak load shifting or various other demand response programs. The system can be configured for particular needs and run on different strategies to achieve numerous goals. 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. Since the technology tested is geared for fast response the value of regulation service provided by a smart electric water heater will potentially increase.

One challenge for this technology may arise from new federal regulations. Starting April 16th, 2015 electric water heaters with tanks larger than 55 gallons need to have an energy factor of 2.057 according to 10CFR 430.32 ‘Energy and water conservation standards and their effective dates.’ 10CFR 430.32 represents a regulatory hurdle for this technology since resistance element water heaters can never run above an energy factor of 1. Efforts from manufacturers are focused on making an exception for smart electric water heaters which use resistance heating elements as the load shifting and regulation ability add operational dimensions beyond ordinary water heaters.

2
INTRODUCTION

Water Heating

Water heating energy use is second only to space conditioning energy use as the highest energy load in residential buildings. It is also a significant load in some commercial and institutional buildings like food service establishments and dormitories. In 2010, 0.53 quadrillion BTU's of electricity was used for water heating in residential and commercial buildings [1].

Adequate hot water at the right temperature is an important factor in user satisfaction. The following table shows some of the terminal hot-water usage devices for both residential and commercial applications.

Table 2-1
Terminal Hot Water Usage devices

Residential Applications	Commercial Applications
Sinks	Sinks
Automatic Dish Washers	Commercial Dish Washers
Clothes Washer	Food Preparation
Bathing	Bathing

Electric resistance heating coupled with an appropriately sized storage tank is the primary means of heating water with electricity. Heat pump water heaters are gaining attention, but their penetration in the water heating market is limited. The discussion in this technical update will be limited to electric resistance water heaters.

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.

In residential applications, average water draw peaks early in the morning and has a secondary peak between 5 pm and 9 pm. Figure 2-1 shows hourly hot water usage (95% confidence level) of a typical family [2].

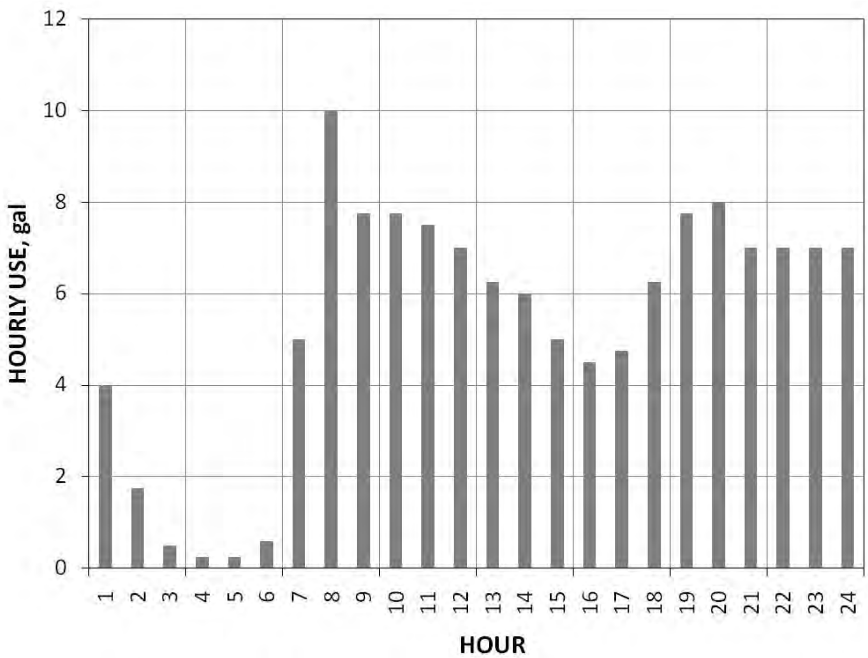


Figure 2-1
Residential Hourly Hot-Water Use, 95% Confidence Level

Electric Water Heater Load Profile

For utilities 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 as seen in Figure 2-1. Figure 2-2 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. Figure 2-4 shows the actual load in PJM region. The peaks in Figure 2-2 align with the peaks on a cold day in Figure 2-4. Modifications to the load profile of electric water heaters can help utilities and grid operators to maintain a better balance between generation and load.

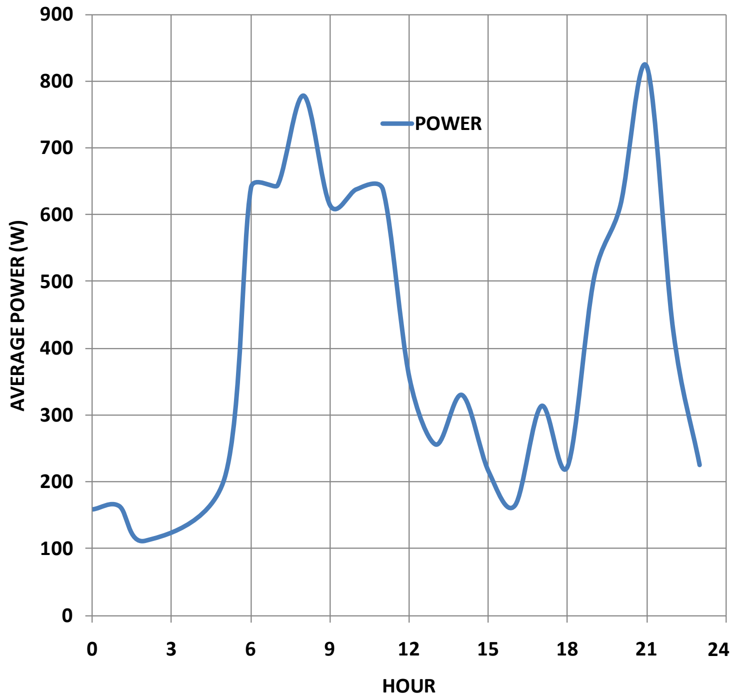


Figure 2-2
Average Power Draw for 7 Days from 4 Field-Installed Resistance Water Heaters

Impact on Electric Utilities

Electric utilities characterize load (energy demand) on their system as base load, intermediate load and peak load. Figure 2-3 shows typical load profile for a day. Base load is the minimum level of demand on the electric supply system over 24 hours. Base load power sources are the plants that provide dependable power to consistently meet demand around the clock, efficiently and reliably. Although base load plants provide reliable and efficient power at low prices, given their size, they are relatively inefficient running at less than full output. Base load plants are predominantly coal fired or nuclear plants that produce electricity continuously.

The intermediate load is satisfied by reasonably sized power plants that are smaller than the base load power plants but larger than the peaking load generators. These plants are called into operation as the load on the grid starts increasing beyond the base load. The schedule of these intermediate plants can be forecasted with high degree of accuracy considering various factors like weather patterns and the demand on the system. For example during night time only base load generators might be operating but as the load on the grid starts increasing starting early morning, these intermediate plants can be scheduled to come online at a particular time.

Peak loads are the loads that go much beyond the load serviced by the base load plants. Peaking generators are typically dispatched when the base and intermediate generation cannot keep up with the load on the grid. These loads usually occur when the customers are using the most power, for example a hot summer day when the air conditioning loads are higher. Peaking generators quickly respond to the changes in the power demand but are expensive to operate from a utility perspective.

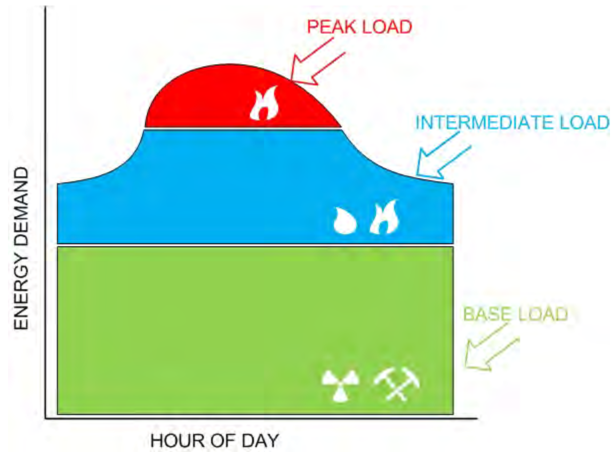


Figure 2-3
Base, Intermediate and Peak Load

Comparing the hot water usage profile from Figure 2-1 and the load curve from Figure 2-3 it is evident that hot water draw coincides with peak load on the electricity grid. Peak load, as discussed earlier is usually satisfied by dispatching the costliest resources in the electric utilities portfolio. Shifting this load to off peak hours can have considerable economic benefit. Figure 2-4 shows the actual load (approximate) for two days, January 31st 2011 and August 31st 2011 in the PJM region. The figure shows the difference in load profile in winter and summer.

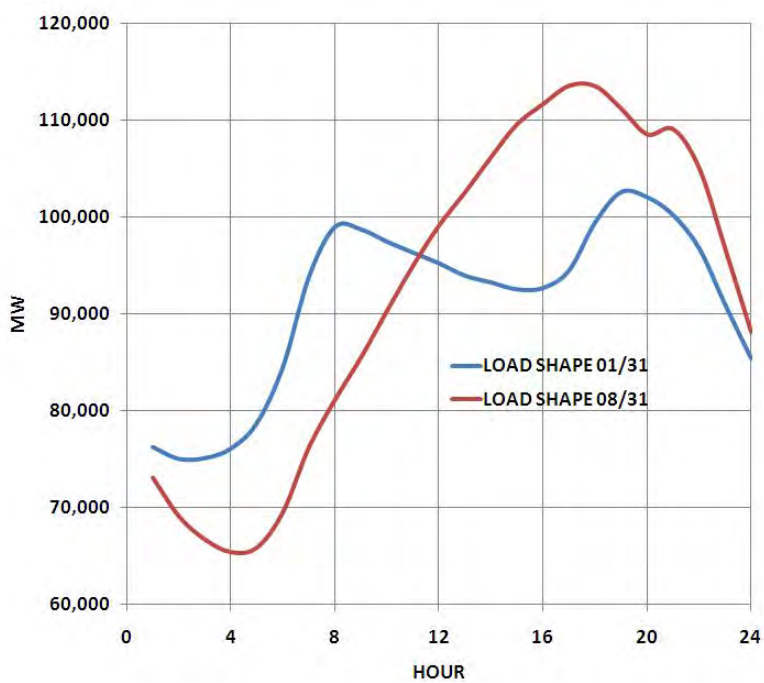
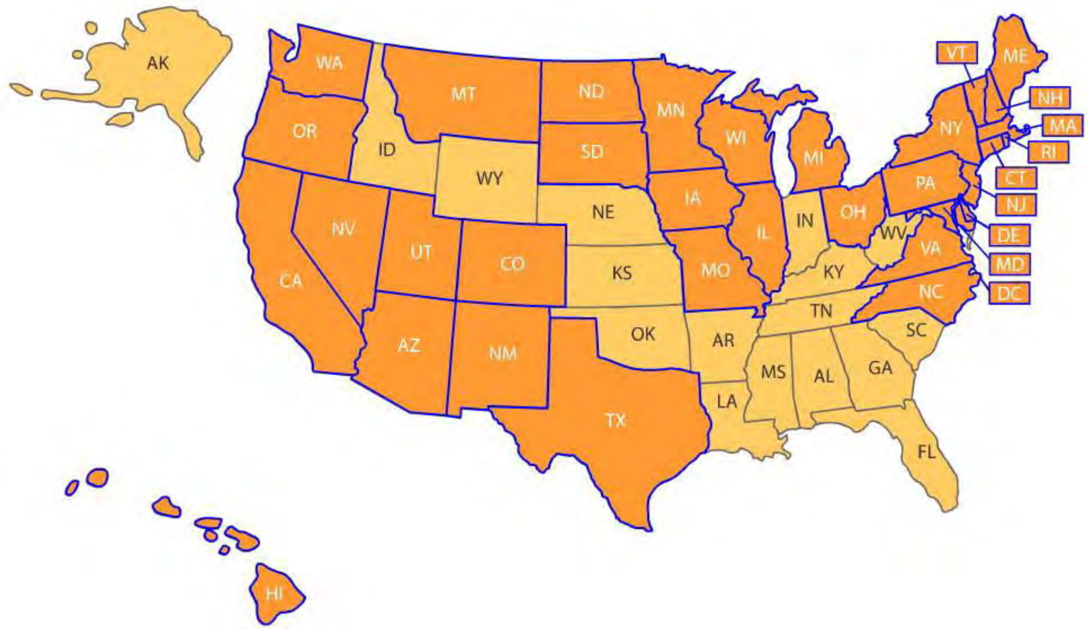


Figure 2-4
Actual Load Shape for Two Different Days in PJM Region

Effect of Renewables on the Electric Grid

Renewable Portfolio Standards (RPS) from numerous states requires utilities to have a greater percentage of their energy generated from renewable resources. Figure 2-5 is a map of the U.S.

which shows states that have renewable energy targets. 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 has its peak output in between mid morning and mid afternoon and wind energy is 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.



Public domain image from U.S. DOE EERE http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm. Orange colored states indicate states with RPS policies whereas light orange states do not have RPS policies yet.

Figure 2-5
Map of the U.S. States with Renewable Energy Targets.

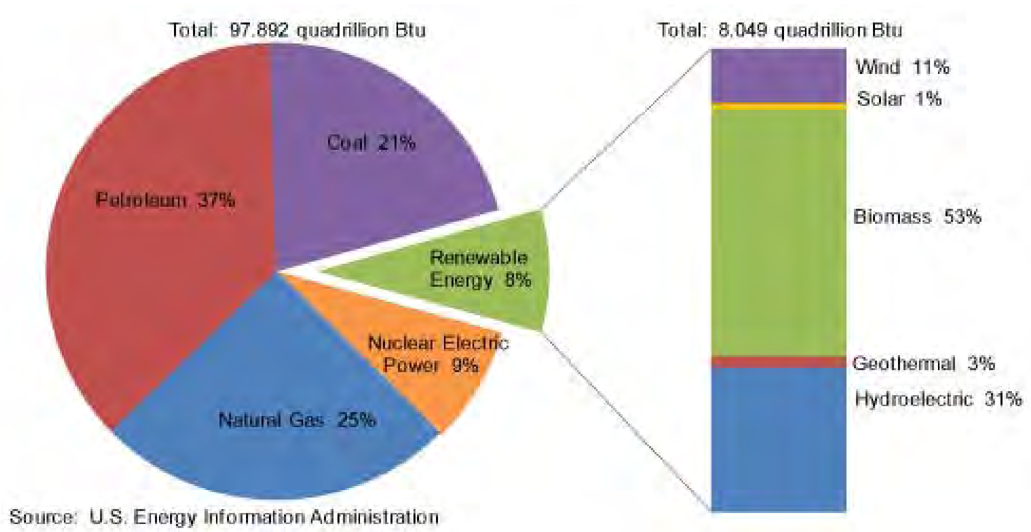


Figure 2-6
Renewable Energy Consumption in U.S. Energy Supply 2010

Integrating Wind Energy into Electric Grid

At the end of 2010 the United States had more than 40,000 MW of land-based installed wind power capacity. Figure 2-7 shows the cumulative total and the yearly addition of wind power in the US market. The interest in wind energy remains high and capacity addition through 2013 is predicted to be in excess of 15,000 MW [3].

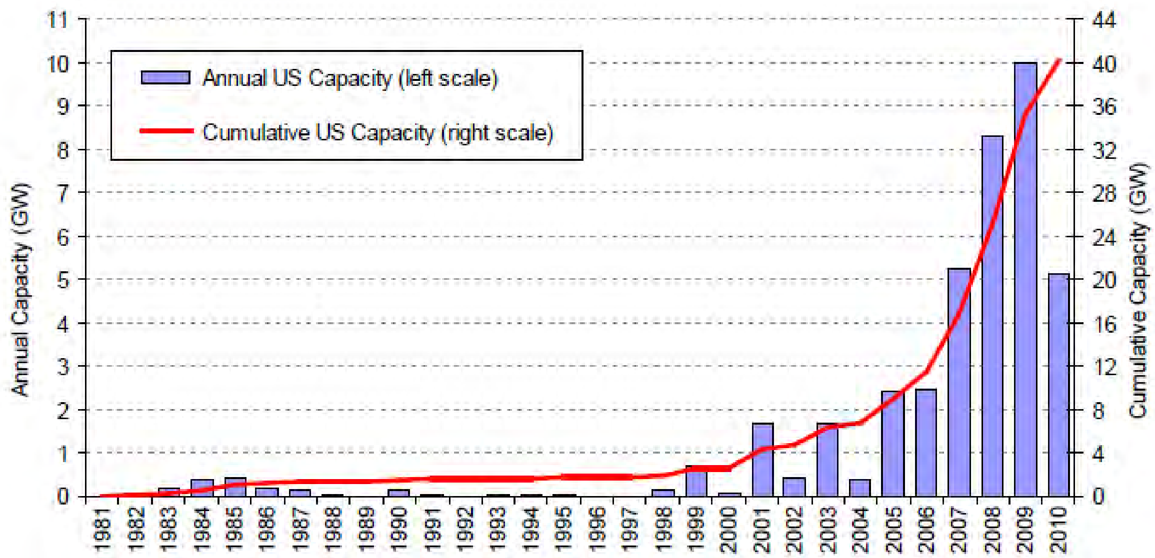


Figure 2-7
US Installed and Cumulative Wind Capacity [3]

One of the important characteristics of wind power is the varying amounts of electricity generated due to wind conditions. 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. Figure 2-8 shows the average hourly wind generation in the PJM region from January through March 2011 [4]. Note that the data shows the actual average hourly generation and does not indicate whether wind generation was curtailed.

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.

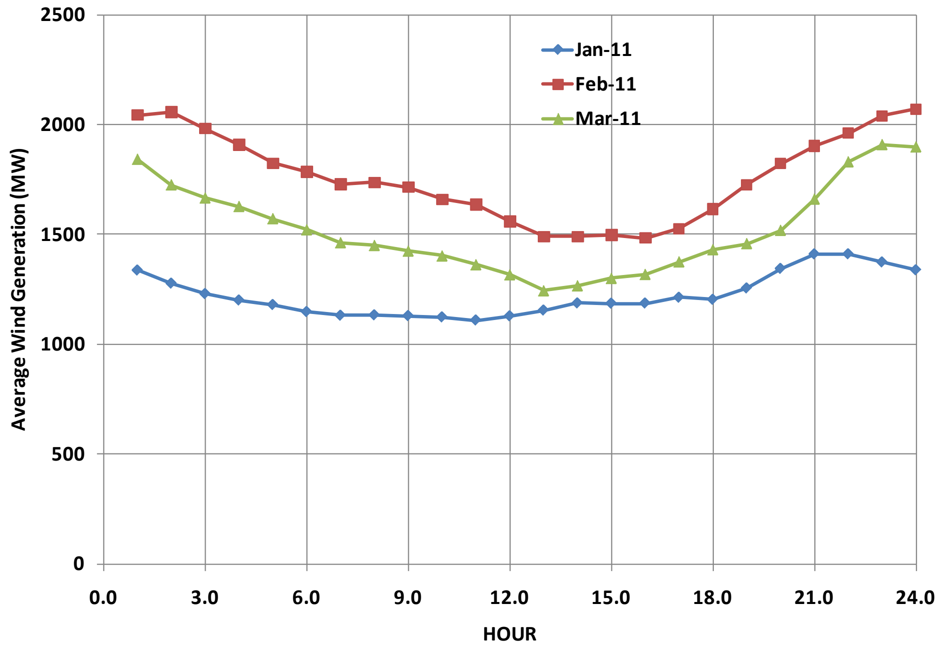


Figure 2-8
Average Hourly Real Time Generation of Wind Units in PJM (January 2011 – March 2011)

Wholesale Electricity Markets

In the 1990's wholesale competition for electricity was established in the U.S. Various utilities and state and federal regulators began forming independent transmission operators to ensure equal access to power grid for new, non-utility competitors. Figure 2-9 shows the operating regions of the 10 Regional Transmission Organizations (RTO's) and Independent System Operators (ISO's) operating within United States and Canada. These entities serve two-thirds of electricity customers in the U.S. and half of Canada's population.

One of the important responsibilities of RTO/ISO's is to maintain reliable system operations in real time. Buyers and sellers of various products and services (for example capacity, reserves, regulation etc.) submit demand bids and supply offers. The markets clear these bids and offers considering various parameters to balance supply and demand while selecting least cost resources.

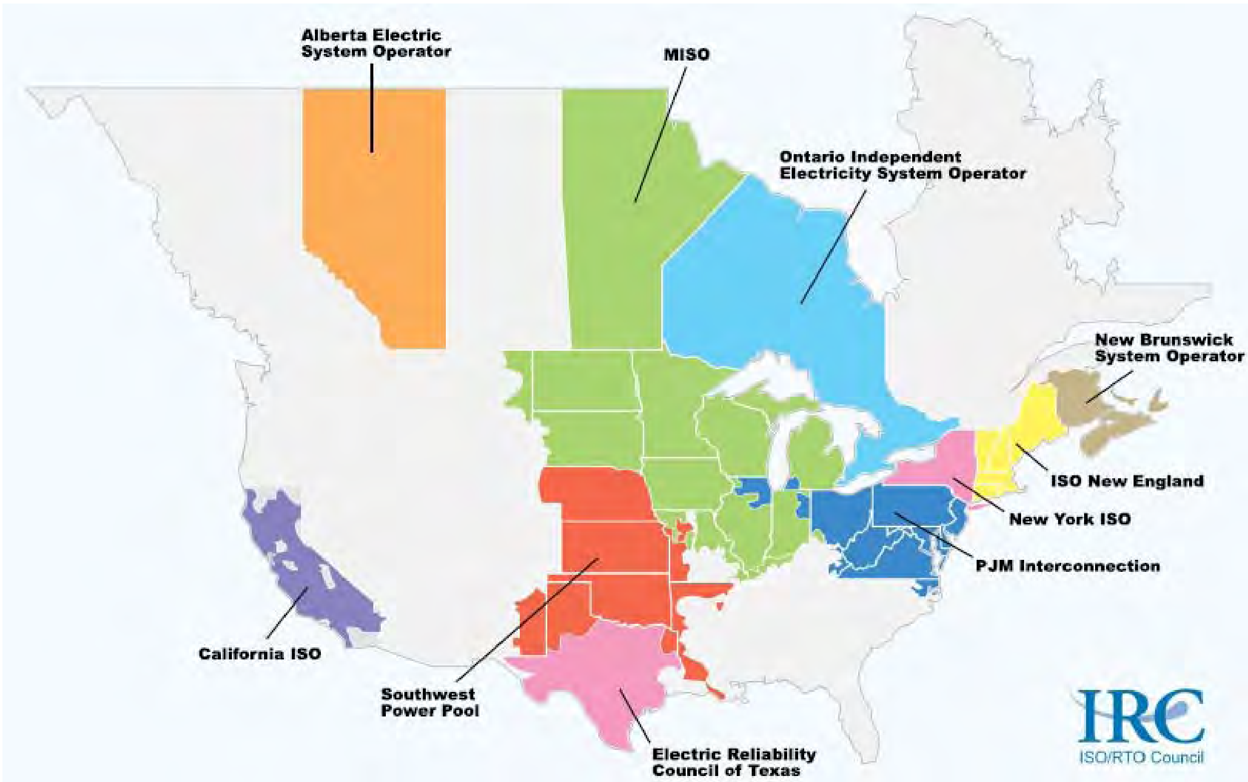
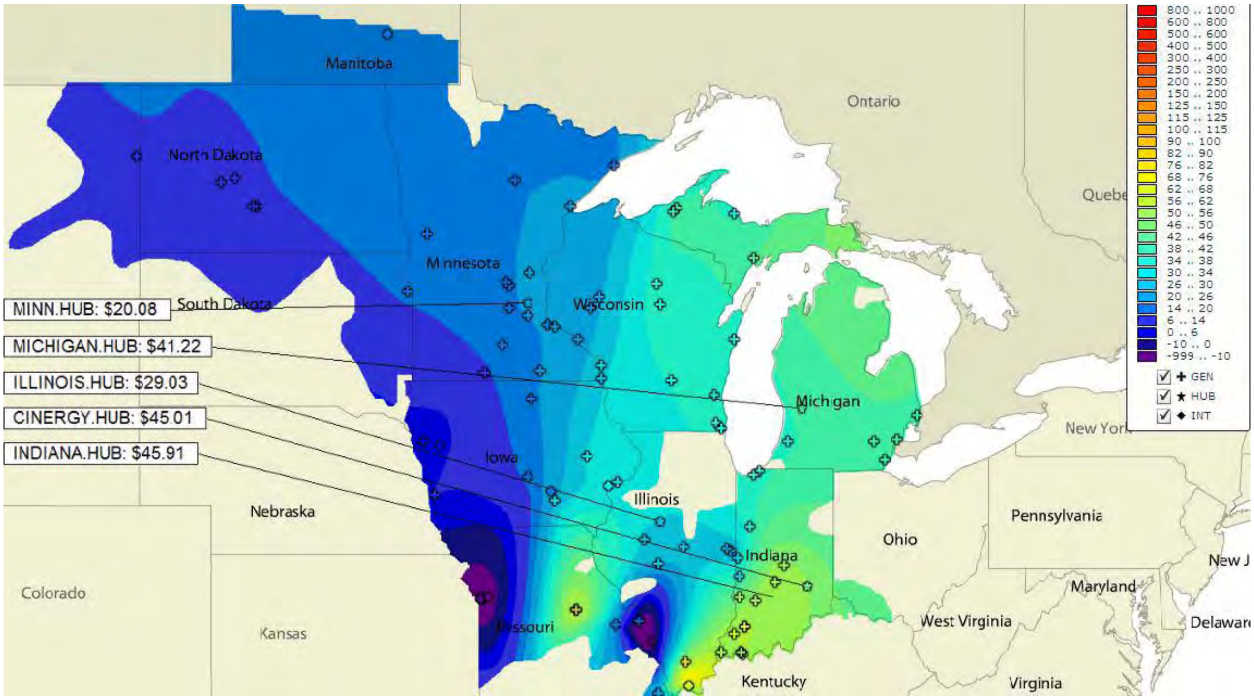


Figure 2-9
ISO/RTO Operating Regions (from ISO/RTO Council)

The ISOs/RTOs resulted in better transparency of the power grid in terms of locational pricing, congestion and reliability. The availability of price signals and adoption of non-discriminatory rules for grid interconnection facilitated private investment in various new technologies. The presence of numerous companies in the market also resulted in more buyers and sellers in the markets. Various markets exist within the ISO/RTO like Energy Market, Ancillary Services, Demand Response etc. Not all markets, products and services are available in each and every ISO/RTO. For the purpose of this report only energy markets and regulation services are discussed.

Energy Markets

Energy markets coordinate the buying, selling and delivery of wholesale electricity. The energy market consists of a real-time market and day-ahead markets. The price of energy varies by location because of the cost associated with delivering electricity to these different locations. Locational Marginal Pricing (LMP) is a way to reflect these locational cost differences. Figure 2-10 shows real time LMP from MISO (Midwest ISO) region. Various regions in MISO have different prices for energy at a given time. The same is true in other ISO /RTO's.



www.midwestiso.org

Figure 2-10
Real Time LMP Contour Map for MISO Region (10/19/2011 – 2:15 PM EDT)

Similar to the real time energy market, there is a day ahead energy market and corresponding day ahead locational marginal pricing (DA-LMP). In day ahead pricing the load curve (demand bid) is supplied by the Load Serving Entities (LSE's) and resources offers are supplied by participants having generating capabilities. The forward market (day ahead) clears the energy for each hour of the next operating day using proprietary algorithms and computer programs. The prices shown in Figure 2-10 are real time prices. The day ahead prices for the same time that were cleared a day before (10/18/2011) are shown in Table 2-2.

Table 2-2
Day-ahead LMP from MISO (10/18/2011 for hour 15)

HUB	PRICE ($/MW)
Illinois Hub	23.27
Cinergy Hub	30.35
Michigan Hub	31.81
Minnesota Hub	17.30
Indiana Hub	30.70

From Figure 2-10 and Table 2-2 the difference in the price of electricity if it is bought a day ahead or in real time can be seen. For example, for the Indiana Hub, day ahead price for hour 15 was $30.70 whereas the real time price at 2:15 PM is $45.91.

Regulation Service

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 and either up or down. These adjustments are called frequency regulation.

Regulation services are further classified on the basis of how quickly resources can respond. For example, in the PJM 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 e.g. 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 (AGC or ACE correction signal) and avoids hunting (overshooting and undershooting) of the ACE correction needs.

Electric Water Heater for Peak Load Shifting

High penetration of electric storage-type water heaters in the U.S. residential market and ease of control makes electric water heaters a preferred 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.

Although electric water heaters present an opportunity for peak load shifting and energy storage, various challenges exist. Recently heat pump water heaters are gaining more attention due to numerous manufacturers introducing and heavily marketing HPWH products. The concept of moving heat from air to water instead of creating heat by resistance elements is resonating with energy and environment conscious customers. Legislative action towards prohibiting use of resistance element heating and incentivizing heat pump water heaters is underway.

10CFR 430.32 'Energy and water conservation standards and their effective dates' requires that electric storage-type water heaters above 55 gallons capacity must have an energy factor of at least 2.057 from April 16th 2015. Resistance water heaters larger than 55 gallons do not satisfy this requirement and would be forced out of the market.

3
ENERGY STORAGE

Energy Storage

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 electric energy storage systems. Electric 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 indefinitely for future use. In electric energy though, storage avenues are limited and expensive. Some of the electric energy storage technologies currently in use are pumped hydro, compressed air energy storage (CAES) and various chemical batteries. Other storage technologies like flywheel energy storage are in trial or demonstration phase.

The current installed worldwide energy storage capacity is over 125GW. Pumped hydro dominates the US and the global market in energy storage. Table 3-1 estimates active energy storage systems in the US [5].

Table 3-1
Active Energy Storage Systems in US

Storage Technology Type	Capacity (MW)
Pumped Hydro Power	22,000
Compressed Air	115
Lithium-ion Batteries	54
Flywheels	28
Ni-Cd Batteries	26
Sodium Sulfur Batteries	18
Other (Flow Batteries, Lead Acid)	10

Thermal Energy Storage

Unlike the technologies discussed in the previous sub-section, thermal energy storage converts electricity into thermal energy. A thermal reservoir is used to store this energy in a suitable medium which is either above or below the ambient temperature. An important distinction between thermal energy storage and other electric energy storage technologies is that the change in form of energy is not reversible. In case of batteries or pumped hydro for example, the electric energy is converted into chemical energy or potential energy which can be converted back to electric energy when required. There are losses involved in this conversion, but the losses are within reasonable limits. In electric thermal storage, the ability to convert thermal energy back to electric energy is lost. From a thermodynamics standpoint, heat is low grade energy. All available thermal energy cannot be converted into work (electricity) without rejecting some of the thermal energy to the sink (atmosphere). For example an internal combustion engine in a car has to reject heat to the atmosphere through the radiator and the exhaust gases. Only a part of the chemical energy (gasoline) we put into the car gets converted into useful work. The obvious question then is to ask why we want to convert electricity into thermal energy.

In 2010, 48.7 % (DOE buildings Energy book) of electricity use in the residential sector was either for space conditioning (heating and cooling) and water heating. Table 3-2 shows the 2010 residential energy end use split in all electric homes [1].

Table 3-2
2010 Residential Energy End-Use

	Energy Use (Quadrillion Btu)
Space Heating (including furnace fans)	0.43
Space Cooling	1.11
Refrigeration	0.44
Water Heating	0.44
Total Residential Energy End-Use	4.97

Data indicates that almost 50% of energy supplied to U.S. homes is converted into some form of thermal energy – either cooling or heating (air or water). This required thermal energy can be stored cheaply.

Thermal energy can be stored as a cold medium, like ice, to provide a cooling effect later when needed. Thermal energy can also be stored in hot ceramic bricks to provide heating to a house when needed. In this case the thermal energy is never converted back to electricity but is used to offset use of electricity at a later time. There are already products on the market that store thermal energy and utilize it as a peak load shifting resource. With the ability to store electricity in the form of thermal energy which will be later used, renewable resources can now be put to charge these thermal storage devices. Besides renewable, cheap electricity at off-peak hours can also be utilized to charge thermal storage devices to lower power consumption during peak periods.

Storing Energy in Ice

EPRI's thermal energy storage efforts from year 2009 and 2010 focused on one such product, Ice Bear [8],[9]. Ice Bear is an energy storage solution specifically developed to freeze water during off-peak hours. The thermal energy storage is made possible by the large heat of fusion on water. Ideally one metric ton of water (one cubic meter) can store 334 MJ of energy (317kBtu or approximately 93kWh). The Ice Bear combines a regular air conditioning system and an additional evaporator coil immersed in water to create ice. During charging cycle, the evaporator coil makes ice in separate storage container and during discharge cycle this stored ice is melted to provide cooling for the conditioned space. EPRI laboratory and field testing has shown that ice storage can effectively offset cooling equipment, in this case providing five tons of on-peak cooling per unit at greatly reduced on-peak power.

Storing Energy in Hot Water

Water heating consumed about 0.44 Quadrillion Btu's in year 2010 (electric water heaters only). In 2007 there were roughly 53 million households (42% of all residential buildings) in the US with an electric water heater [17]. Storage-type electric water heaters contribute 99% of the total installed electric water heaters. The penetration of tankless water heaters is 1%. This wide installed base of water heaters is a perfect opportunity for storing hot water close to the point of use [1].

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 also 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 125ºF can store about of 8 kWh of energy. Assuming an average storage size of 50 gallons and thermostat set at 125ºF and cold water temperature of 60ºF the 53 million households that have electric storage water heaters have an aggregated thermal battery of 400 GWh. This is a tremendous resource and has potential to contribute in the thermal energy storage arena.

Currently few efforts have been made to use this huge thermal storage battery. Demand response and peak load shifting programs that exist use a preliminary ON-OFF control. Great River Energy has 63,000 water heaters enrolled in their peak load shifting program.

Table 3-3
Great River Energy's Water Heater Curtailment Program

	Peak Shave Water Heating Program	Off-Peak Water Heating Program
Strategy	Peak reduction	Valley filling
Number of Customers	37,800	58,000
Peak Reduction Capability	~20 MW	50MW Year round
Curtailment Period	4-8 hours when needed	7 am – 11pm Weekdays

Tennessee Valley Authority and Bristol Tennessee Essential Services had a water heater control demonstration with 117 water heaters on an ON-OFF control. Portland General Electric Company did a study of 81 participants in their 'Direct Load Control Pilot for Electric Water Heat' program. Florida Power and Light has a residential load control program that includes electric water heaters. Several other utilities have demand response programs that include electric water heaters [6].

4
STRATEGIES FOR PEAK LOAD SHIFTING USING THERMAL ENERGY STORAGE

An electric storage water heater can be envisioned as an energy storage device with its capacity specified in kWh. Various strategies can be implemented for effective charging of the water heater. A few charging strategies are discussed in this chapter starting with the basic strategy of a regular water heater. Beyond the regular water heater strategy advanced strategies are also discussed. Before the strategies for thermal energy storage are elaborated, a distinction is made between regular water heater and a smart electric water heater.

Regular Water Heater

A regular water heater is a resistance type storage water heater commonly found in U.S. residential applications. This type of water heater has no communication capabilities. The charge rate on such a water heater is constant and is determined by the resistance heating element installed on the water heater. A regular water heater has no charge detection mechanism other than the thermostats to determine if the water heater is fully charged.

Smart Electric Water Heater

A smart electric water heater is a resistance type storage water heater with added controls, instrumentation and communication capabilities. The advanced control allows the charge rate on a water heater to be varied. With this capability, the water heater can not only charge at the maximum rate but at any rate in between determined by the controller. In a regular water heater the charging rate cannot be controlled. When the heater elements come ‘ON’, the heaters draw full rated power and cannot be modulated. With a smart electric water heater, the power to the heating elements can be modulated by using controls installed on the water heater. This capability can be used to reduce instantaneous power draw and charge the water heater over a longer period. The instrumentation includes internal temperature sensors (thermocouples) and power monitoring device. The temperature sensors provide an accurate picture of the charge level in a water heater which helps in determining the charge rate and the time to charge. Temperature sensors also act as a safety mechanism in case the water heater is set to store water at temperatures higher than 140ºF. In situations where higher water temperature is set for storage a separate mixing valve is installed to temper the water before it is supplied to various end use devices. Power monitoring is also added for auditing purposes in various strategies where the smart electric water heater might be providing a regulation or demand response services. Two way communications with a system operator or an aggregator is also necessary for smart electric water heater to implement various charging strategies.

Charging and Discharging a Regular Water Heater

We will continue with the example of the 50 gallon water heater with thermostat set at 125ºF. When the water heater is fully charged i.e. the thermostat is satisfied and the heating elements are not drawing any power, the total charge in the water heater is 8kWh. Drawing water out of the water heater at this time is equivalent to discharging the water heater. As hot water gets drawn, the charge in the water heater reduces. In a regular water heater, the control system is a simple thermostat that makes or breaks a mechanical switch. The proxy for charge in a water heater is the water temperature. As hot water is drawn out and cold water enters the tank, thermostat in the water heater senses a drop in temperature and starts the charging process. In this control strategy the water heater is not connected to any external communication channel and runs entirely by itself. Figure 4-1 shows a schematic of the charge and discharge process in a regular water heater.

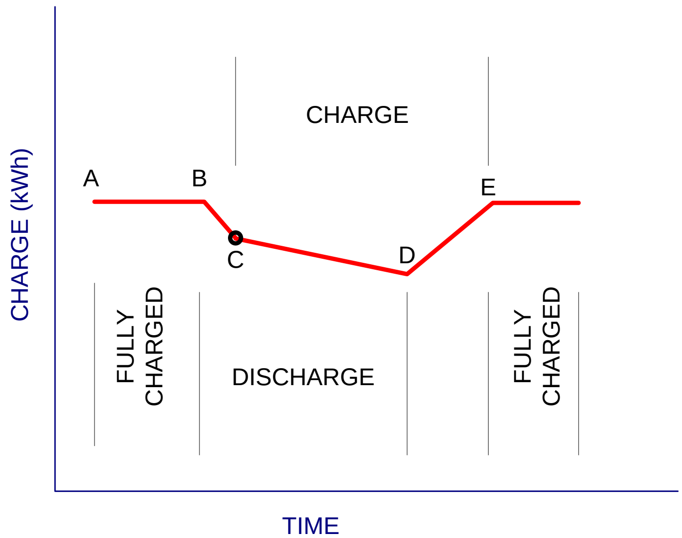


Figure 4-1
Charge and Discharge Process in a Regular Water Heater

From Figure 4-1, at point B, the water heater is fully charged. As water is drawn from the tank the discharge process starts between points B and D. Point C is the point where the thermostat closes and the water heater starts drawing power to heat water. This is the point where the charging process starts. Point C is an important point – it shows that the water heater doesn't immediately start charging when it is discharged. The water heater reaches a certain charge level below the fully charged level before the charging begins. Another important point to note about the point C is the discharge level. The water heater hasn't discharged significantly before the charging commenced. Total discharge was [Charge at point B – Charge at point C]. This shallow discharge before the charging commences makes the water heater power draw curve follow the hot water draw curve. Between points C and D the water heater is charging and discharging simultaneously. In between points D and E the discharging has stopped and the heating elements are charging until the thermostat is satisfied.

The charging rate is dependent on the heater element wattage. The discharge rate depends on the hot water draw. It should be noted that the slope of the line from point B to C to D is dependent on the hot water draw whereas the slope of line from D to E is dependent on the wattage of the heater element.

Peak Load Shifting Using Regular Water Heater

The problem with the control strategy on a regular water heater is the power draw following the hot water draw. The hot water draw in residences coincides with the peak load on the electric grid. One way to get around this problem is to delay the charge cycle by interrupting the power supply to the water heater. Figure 4-1with this interrupted power supply will now look like Figure 4-2

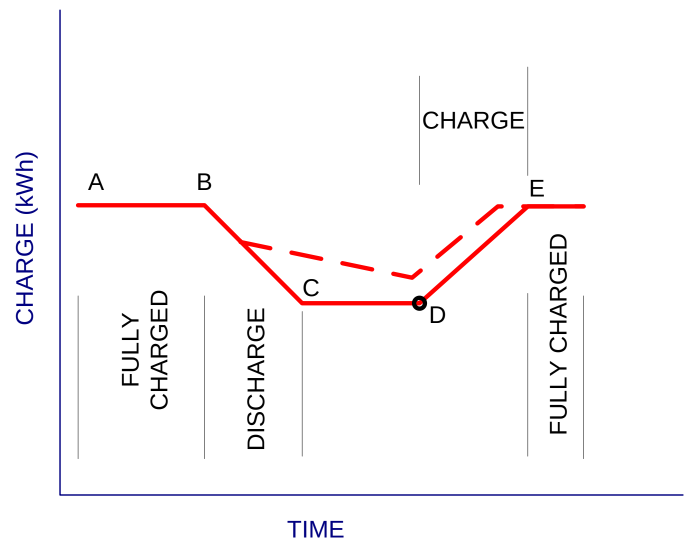


Figure 4-2
Peak Load Shifting using Regular Water Heater

The difference between the two figures is the point where the charging begins. In Figure 4-1the charging starts at point C whereas in Figure 4-2 the charging starts at point D. Note that the slope of the charging line is still the same as what was before (shown as a dotted line). The important factor here is the control of point D which is now externally controlled. This can be done by the electric utility or a third party who has access to the water heater. With the control on when the water heater has power available, the utility can now shift the load to off –peak hours or any particular hours of the day depending on the requirements. In case the charge level drops substantially, a temporary boost might be given to eliminate user complaints. The important distinction here is that the water heater does not account for the charge level. In such a situation the control of point D is critical because the water heater might run out of all the hot water without it ever starting to charge.

Optimizing Locational Marginal Pricing

Charging water heaters at off-peak hours is a strategy that has been implemented since the 1980’s. With the advent of energy markets and the accessibility to the real time market data an advanced strategy based on LMP’s can be implemented. The real time price of energy is higher when there is high load on the grid or generation is constrained or any other factor. The LMP reflects these high prices at various locations. If a water heater is allowed to charge only when the LMP’s are low then the water heater will run in an economically efficient way.

Figure 4-3 shows real time LMP values at a node in MISO.

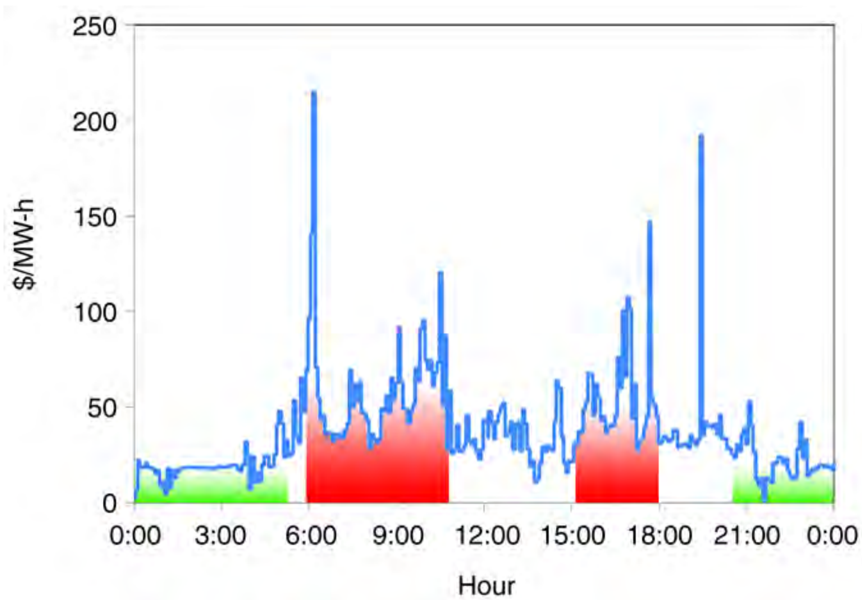


Figure 4-3
Real Time LMP Values at a Node in MISO on October 18th, 2011

Figure 4-3 shows the price of energy at any particular time during the day. From the prices seen a water heater can be charged at point when the LMP values are low (shown in green). A look at the LMP values also shows that the prices are low at night time and in early morning. This is very similar to various peak load shifting strategies that were implemented previously. With access to real time LMP values a decision can be made to charge during the day if the prices fall below a certain level.

To make this strategy work, a smart electric water heater is required. Smart electric water heater has two way communications (with the utility or a third party) and controls implemented at the water heater. An important parameter for a smart electric water heater is the charge level. This is necessary to eliminate the problem of running out of charge. With thermocouples embedded inside the water heater the charge level can be determined. A Low LMP value is a relative term. One way to determine periods of low LMP is to look at average LMP values for a given hour for last ‘n’ number of days (for e.g. 14 days). Figure 4-4 shows average LMP values for past 14 days. From the figure it can be concluded that hours between 11pm and 5am have low LMP’s and can be used for charging the water heater.

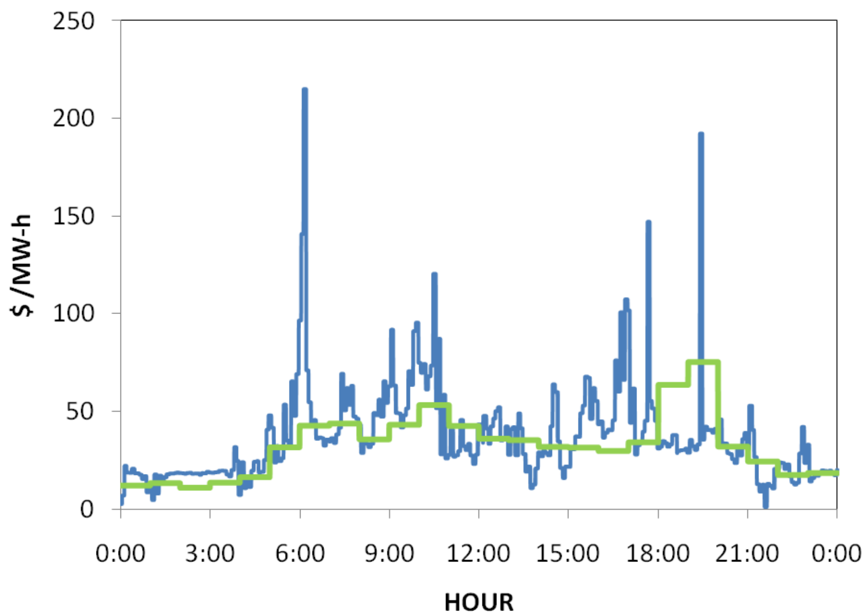


Figure 4-4
Real Time LMP's and Hourly Average LMP (Green) for Past 14 Days

Regulation Strategy

A smart electric water heater can be utilized to provide regulation service to utilities for the purpose of grid management. A smart electric water heater with its two way communication capability and the ability to monitor charge in the water heater can be used to provide fast acting regulation service to provide effective frequency control. In regulation strategy, the smart electric water heater can be set to draw power at half the rated power draw when the water heater elements are 'ON'. For example if the heating elements are rated at 4.5kW, the heating elements are set to dissipate 2.25 kW at normal condition. This gives the controller the ability to modulate up or down on power.

The signal to the controller to increase or decrease the charging rate can be provided by the utility or the RTO / ISO. Area Control Error (ACE) is the difference between the supply and demand of electricity. The automatic generation control (AGC) signal dictates the generation units following AGC to regulate up or down. If this signal is provided to the controller of a smart electric water heater, the heating elements can be modulated to provide a similar 'up' or 'down' regulation. For example if one thousand smart electric water heaters with 3 kW elements are aggregated to a total of 3 MW, the charge rate can be modified to anywhere between 0 MW and 3 MW.

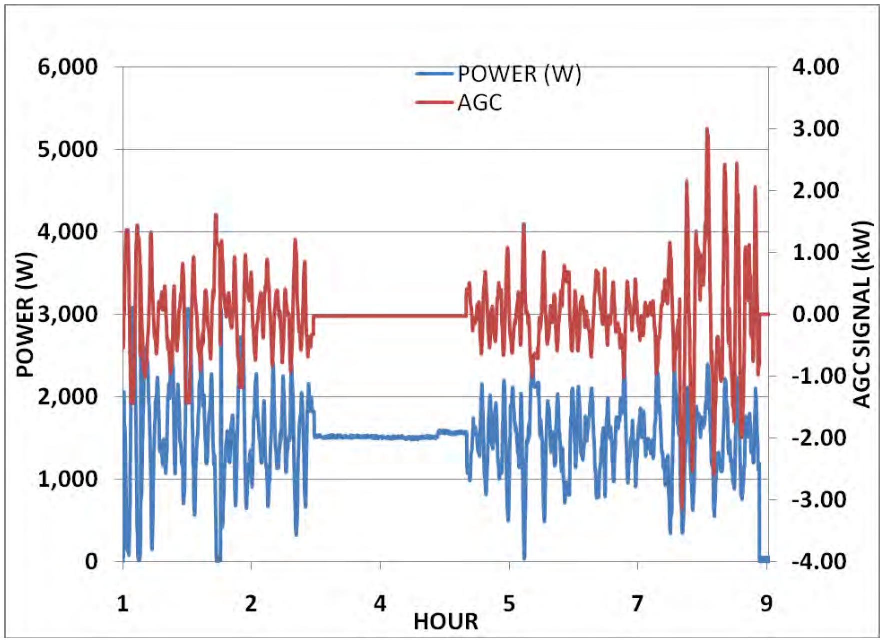


Figure 4-5
Power Draw from a 3kW Water Heater and Associated AGC Signal

Figure 4-5 shows actual operation of a water heater running the regulation strategy. The AGC signal is a complimentary signal – when the AGC goes positive, the smart electric water heater sheds the load i.e. reduces power draw and vice-versa. Depending upon the RTO/ISO or the third party controlling the water heater the AGC might be a different signal but the overall concept stays the same.

Regulation is an ancillary service and the providers get compensated by the system operators. Providing regulation service at off-peak hours has further economic benefit for the utility or the aggregator. During off-peak periods base load generators that are dispatched are already running minimum load. These generators can provide up regulation but cannot provide any further down regulation. Depending upon the RTO/ ISO these generators cannot bid into the regulation market since they cannot provide both up and down regulation. Smart electric water heaters, on the other hand can provide both up and down regulation and bid into regulation markets when the regulation capacity is constrained.

Balancing Reserves Deployed Strategy

The Bonneville Power Administration (BPA) has a Balancing Reserves Deployed (BRD) signal which is used to balance renewable energy resources and demand variations with generation sources. This is the difference between predicted wind and actual wind generation in the area. When the Balancing Reserves Deployed signal is positive, it indicates that generation is increased to balance the grid and when the signal is negative, it indicates that generation is decreased to balance the grid. One application of this signal can be to use it in conjunction with a smart electric water heater. The action by the smart water heater can be complimentary to the balancing reserves deployed signal. When BRD signal is positive, the smart electric water can avoid charging whereas when the BRD signal is negative the smart water heater can start charging. The complimentary behavior of a load is equivalent to response from a generating asset for a given BRD signal.

Various other strategies can be implemented depending on the nature of the signal received from the RTO / ISO. A combination of above mentioned strategies can also be implemented to derive benefits of multiple strategies.

5
PRODUCT OVERVIEW AND TEST SETUP

Product Overview

A Grid Interactive Water Heater (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 setup at Steffes. Figure 5-1 shows the basic system provided by Steffes Corporation.

Figure 5-1
Steffes Corporation – Grid Interactive Water Heater

Figure 5-2 shows a schematic of the same setup.

Figure 5-2
Schematic of Steffes Grid Interactive Water Heater

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. The water tank has six thermocouples inserted at various depths to record temperature distribution within the tank. The thermocouple setup is provided by Steffes. 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.

A typical water heater with two heating elements doesn't run both the elements at the same time. The water heater under test heats the upper element first to satisfy the upper thermostat and then runs the lower element to satisfy the lower thermostat. Hot water is drawn from the top of the storage tank. Since the upper thermostat is satisfied first, hot water is readily available. Cold water is introduced in the bottom of the storage tank. As hot water is drawn from the top of the storage tank cold water fills in from the bottom. During normal operation, this turns on the lower water heater element first and if the water draw is high enough, turns on the upper element later. In the current setup, the upper thermostat is set at 170ºF and the lower thermostat is set at 155ºF. The higher water temperature allows the smart electric water heater to store more energy. 170ºF 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 our setup the temperature is set at 123F for the mixing valve. This is the temperature one would otherwise set the thermostat at on a normal water heater.

The netbook is connected to the Steffes 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 communication between the water heater controller and the RTO/ISO is shown in Figure 5-3. A screen shot from the netbook is shown in Figure 5-4. The screen shows the available charge in right top corner along with the reserve capacity. The sum of available charge and the reserve capacity is total storage capacity of the installed water heater. The left top corner shows the current power dissipation of the resistance elements in the water heater. The screen shot shows that the power draw was close to 0W. The up regulation capacity and the down regulation capacity are also shown in the top left corner. The sum of up regulation and down regulation is the total wattage of the heater installed in the water heater. The centre strip chart shows the day ahead locational marginal pricing (DA-LMP). The bottom strip chart shows the power draw. In this instance it can be observed that the power draw coincides with the lowest DA-LMP values.

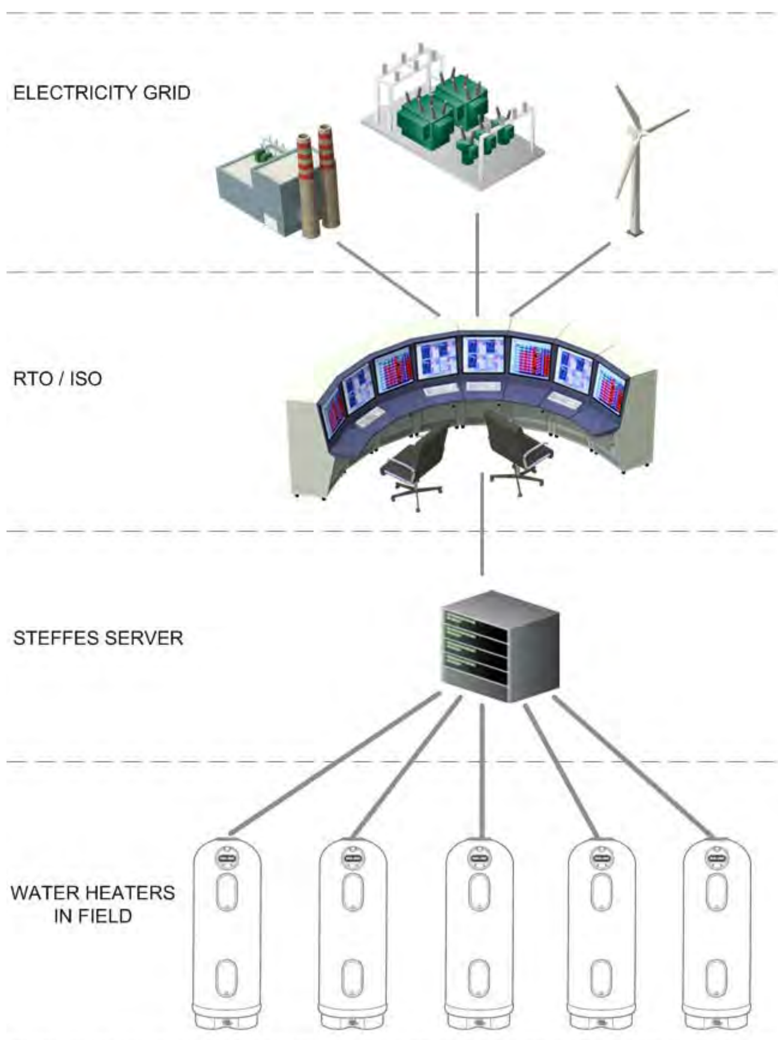


Figure 5-3
Communication between Water Heater, Steffes Server and the ISO/RTO

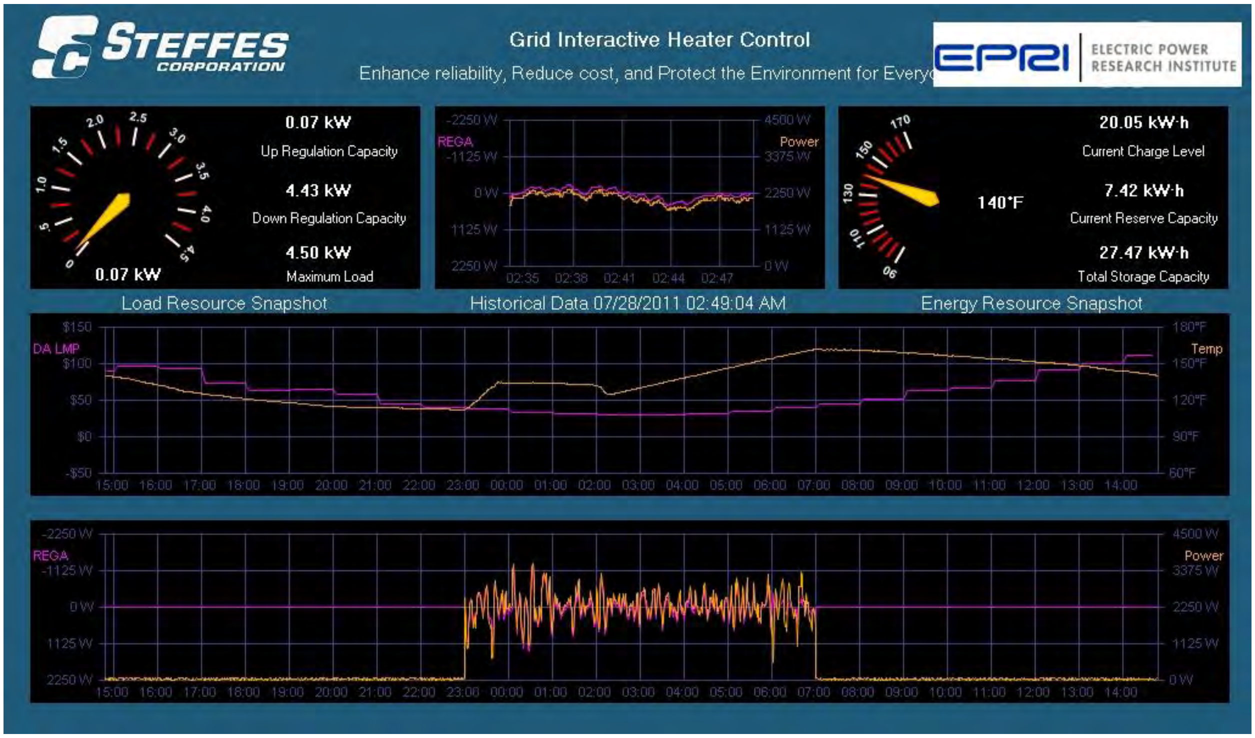


Figure 5-4
Screen Capture from Steffes Netbook Connected to the Water Heater

EPRI Instrumentation

Additional instrumentation is installed and connected to a separate EPRI data acquisition computer. This computer monitors the water inlet temperature, hot water temperature and the mixed temperature of water after the mixing valve. This computer also has the ability to simulate water draw from the water heater according to a predefined hourly profile. 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 5-5.

Two solenoid valves are installed; one on the cold water line and one on the mixed water line carrying hot water. The solenoid valve on the cold water line is set to be normally open (NO). This solenoid valve is a safety valve to avoid flooding the lab in case of a water leakage from the tank. The entire water heater setup is housed in a drain pan which has a float switch. If there is a leak, water will collect in this drain pan and eventually trip a float switch which will shut off the cold water solenoid isolating the water heater from the main water supply. The solenoid on the mixed water line is a normally closed (NC) valve and is controlled by the data acquisition computer. A water draw curve is provided as an input to the software which turns the solenoid valve on and off at predetermined time. The water flow meter installed on the cold water line acts as a counter to compare the water draw to the input water draw curve.

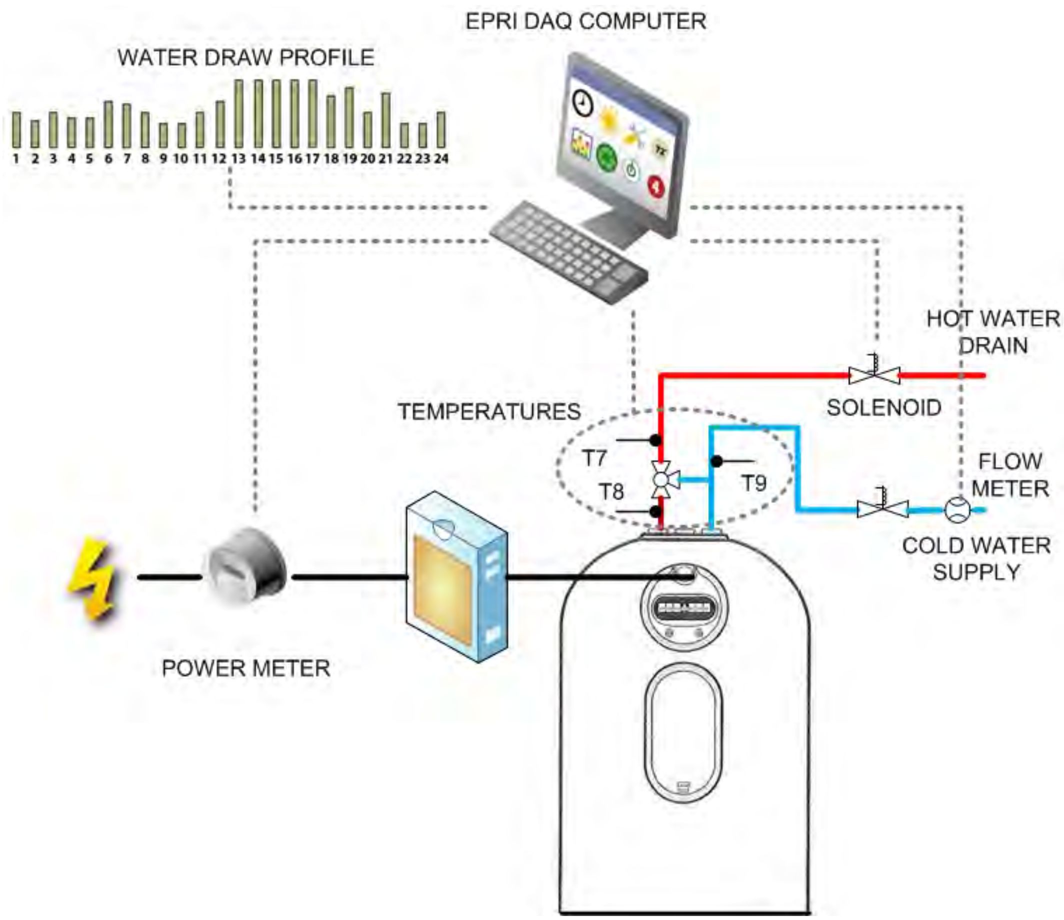


Figure 5-5
Schematic of EPRI Instrumentation

A list of sensors used in the test setup is provided in Table 5-1. All the sensors communicate with the computer through a FlexIO unit from Obvius. Figure 5-6 shows an Obvius FlexIO unit. The FlexIO unit communicates with the DAQ software on MODBUS protocol. The temperature sensors, power meter and the flow meter all can be connected to the FlexIO. The FlexIO also has relay output which is used to control the mixed water solenoid valve.

The three thermistors installed are insertion type Veris brand 10K Dale type. Figure 5-7 shows the thermistors installed on the cold and the hot water lines. The thermistors are installed in a way that the water flow is over them i.e. the direction of thermistor insertion is counter to the flow of water.

Table 5-1
Sensor List

Item	Manufacturer	Parameters Measured	Comments
Power Meter	Wattnode	Power	
		Voltage	
		Energy	
		Current	
Thermistors	Veris	Temperature	3 Total, 10K Dale
Flow Meter		Water flow rate	

Figure 5-6
FlexIO Module from Obvius

Figure 5-7
Thermistors Installed on Hot and Cold Water Line

Figure 5-8 shows the screen shot from the EPRI data acquisition computer. All the data acquired is displayed in real time along with an input section for water draw profile. Data is recorded every 10 seconds. The parameters recorded in the data file are:

1. Date
2. Time
3. Flow meter count at start of experiment
4. Gallons of water drawn from the start of experiment
5. Gallons of water drawn at a particular hour
6. Flow meter count at every 10 second interval
7. Cold water temperature
8. Hot water temperature
9. Mixed water temperature
10. Ambient temperature
11. Volts A-B
12. Energy
13. Power
14. Amps A
15. Amps B
16. Position of hot water solenoid (0=OFF, 1=ON)

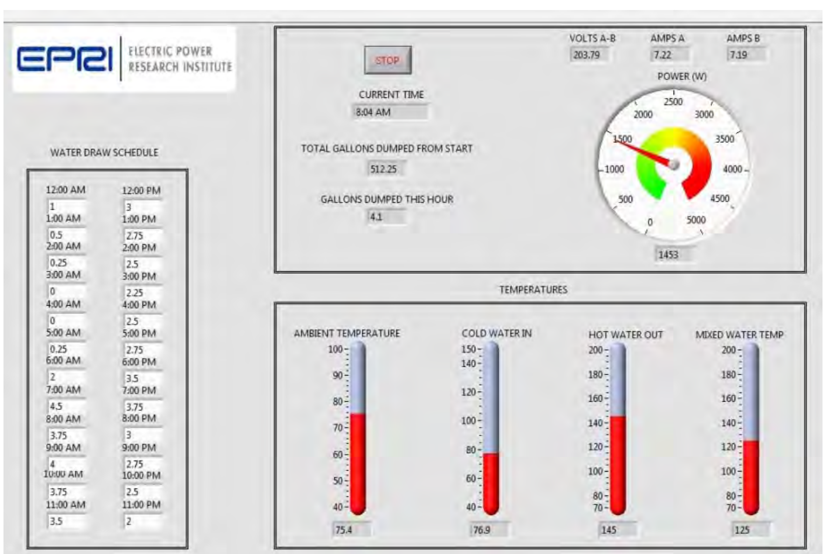


Figure 5-8
EPRI Data Acquisition Display

Communication

The smart electric water heater relies on the real time communication between the controller and remote server which can be hosted by utilities or by a third party. The communication link is established by using the wireless network at EPRI which lets the netbook computer from Steffes Corporation connect to the remote Steffes server.

This communication is critical in order to gain benefit from the advanced control strategies. In lab tests the smart electric water heater was aggregated with a fleet of 3 other water heaters at different locations. The Steffes server aggregated these water heaters and communicated with different servers from PJM, MISO and BPA.

Communication protocol and reliability needs to be stress tested before installing thousands of these in the field. Strategies for communication failure between both the aggregator and the smart electric water heaters and between aggregator and the ISO/RTO need to developed and tested.

6
TEST RESULTS AND ANALYSIS

The smart electric water heater is evaluated by running various control strategies implemented by Steffes Corporation. The grid interactive water heater is also evaluated as a standard water heater by disconnecting the control box and wiring the water heater as a standard water heater. In the case of the standard water heater control strategy, both thermostats on the water heater are set at 125ºF, the temperature otherwise provided by using the mixing valve.

Test Plan

The test plan consists of a fixed water draw profile that is controlled by the EPRI data acquisition computer and running each control strategy for 5 days. Figure 6-1 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 [2]. 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

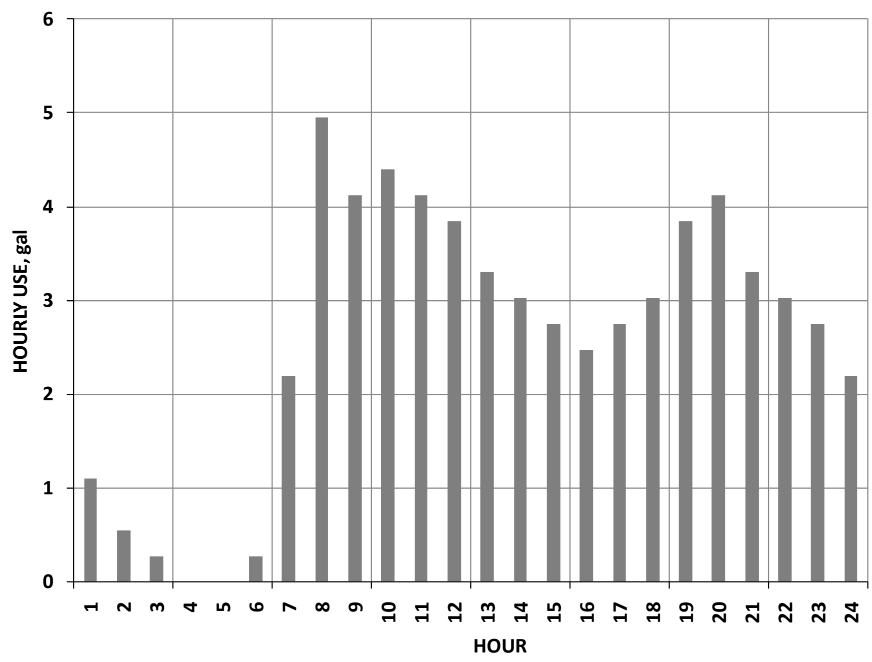


Figure 6-1
Water Draw Profile Used in Testing Grid Interactive Water Heater

Regular 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 6-1 is imposed with the help of EPRI DAQ computer. The thermostats in this strategy are set to 125ºF and no external control is implemented to control the water heater elements. Figure 6-2 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 125ºF because of small error in the thermostat setting.

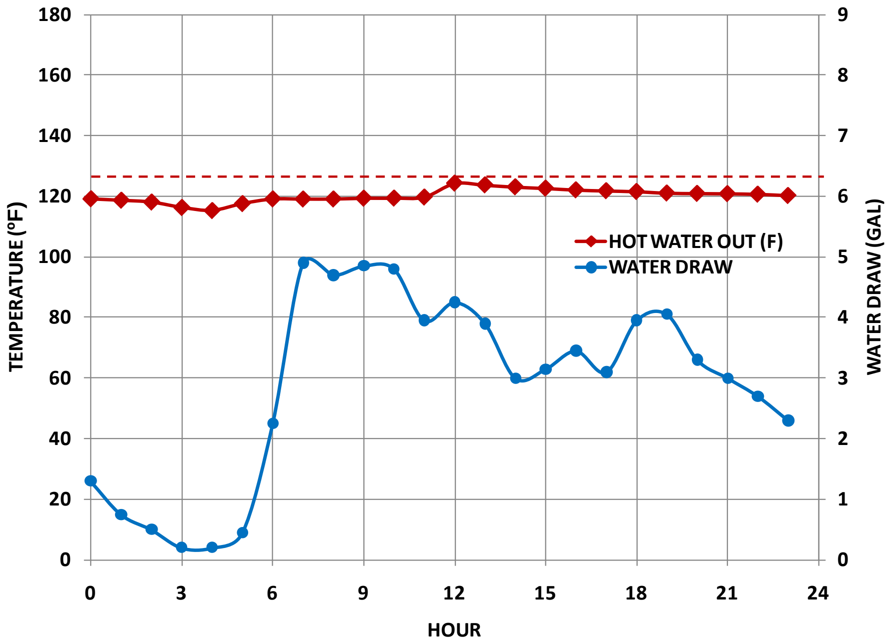


Figure 6-2
Hot Water Temperature and Water Draw

The power draw and energy corresponding to the water draw in is shown in Figure 6-2 is shown in Figure 6-3. The figure shows that the power draw follows the water draw closely. As soon as there is water drawn from the water heater the heating elements come on and re-charge the heater. This situation is shown in Figure 4-1. 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 6-3 that the power draw is always 3 kW which is the rated power for the heating elements at 208V.

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 $ 111.40 to operate per year [Appendix A]. In the operating cost calculation the water draw profile and the DA-LMP curve is assumed constant for the whole year.

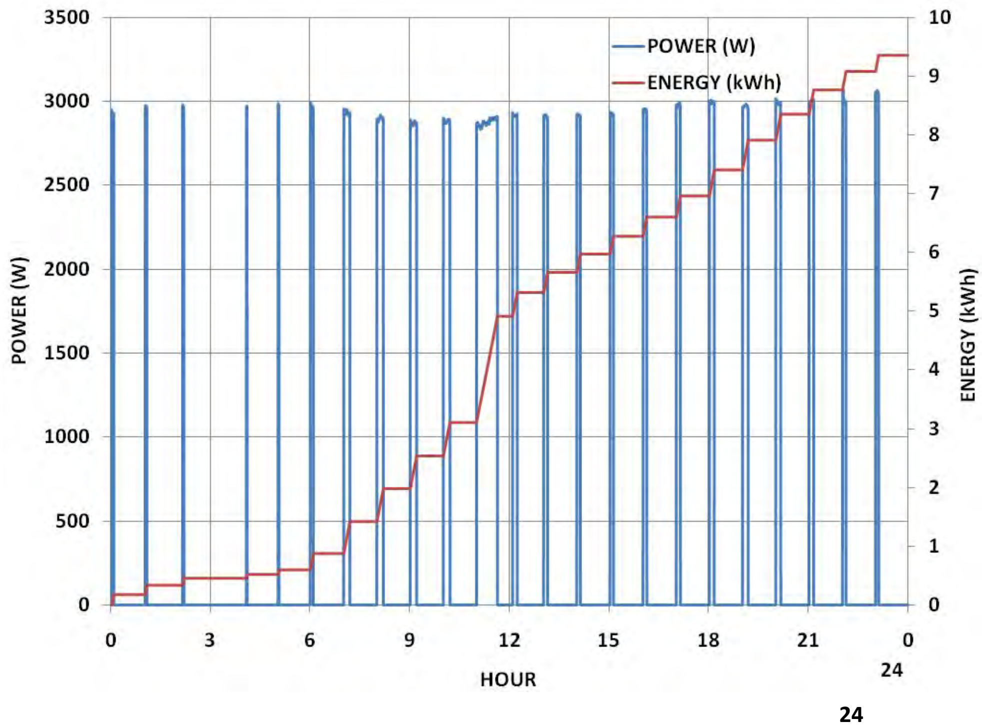


Figure 6-3
Power Draw and Energy for Regular Water Heater

Optimizing Locational Marginal Pricing

When the water heater is wired through the control box, the water heater can be utilized as a smart electric water heater. In a smart electric water heater, the top thermostat on the water heater is set at 170ºF and the bottom thermostat is set at 155ºF. This allows the water heater to store more charge than would be possible when thermostats are set at 125ºF.

Optimizing locational marginal pricing strategy is implemented by receiving real time LMP values from MISO. In this strategy, the real time LMP value is communicated from the Steffes server to the Steffes netbook on the test setup every 20 seconds. The real time LMP values are updated by MISO every 5 minutes. The control algorithm factors in the current charge level in the water heater and the LMP values as they are received from the server.

The charge level is determined by the following equation

CHARGE = $(T_h\text{-}T_c)$*rho*gal*C_p/3600 **Eq. 6-1**

Where:

CHARGE is charge stored in kWh

T_h is the average hot water temperature in the water heater in degrees Kelvin

T_c is the cold water temperature in degrees Kelvin (in the Steffes program this temperature is set at 288.7K or 60ºF.

rho is the density of water at a given temperature in kg/gal

gal is the water storage in gallons (85 gallons for the test unit)

C_p is the specific heat of water at a constant pressure (4.1814 kJ/kg-K)

The total charge capacity of the smart electric water heater is 22.24 kWh if the water is stored at a temperature of 170°F.

For determining the appropriate time to charge the water heater, the control algorithm continuously monitors the charge and the LMP values. A running average of the real time LMP values is also kept as a comparison to the instantaneous LMP's. These values give an idea if the LMP's are favorable or not. During favorable conditions and depending upon the charge level the water heater is scheduled to charge. Figure 6-4 shows the LMP and average LMP values for a 24 hour test period. The LMP is lower than the average LMP in early morning hours, in between noon and 6 pm and between 10 pm to midnight. The control strategy picks up the hours to charge depending on the charge level in the water heater and the LMP values. The power draw during this 24 hour period is shown in Figure 6-5.

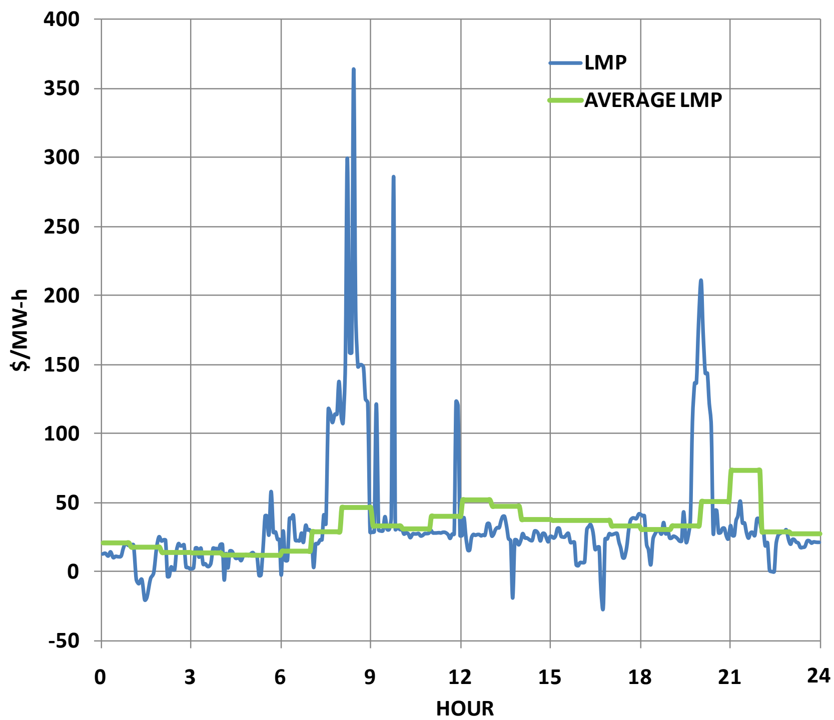


Figure 6-4
LMP and Average LMP Values for a 24-Hour Period

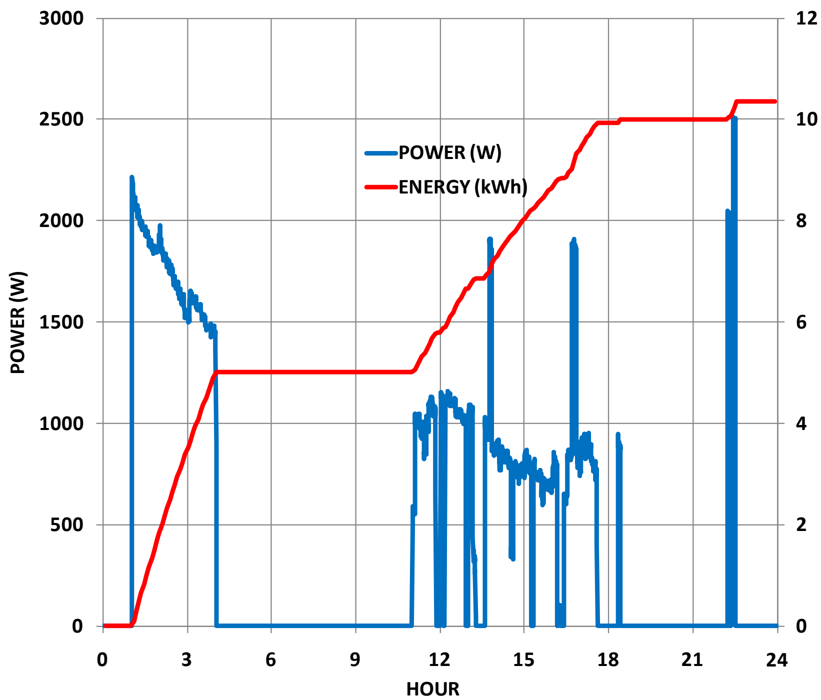


Figure 6-5
Power Draw and Energy when Using Optimizing LMP Strategy

The power draw from the smart electric water heater clearly coincides with the time when the LMP is lower than the average LMP. The charge added to the water heater is shown in terms of energy in Figure 6-5. The smart electric water heater charges less frequently and can vary the charging power as seen in Figure 6-3 and Figure 6-5. The total energy consumed by the water heater is 10.33 kWh.

The water draw and hot water temperature are shown in Figure 6-6. The water temperature is measured at the outlet of the water heater and is not the supply temperature. The supply temperature is lower because of the mixing valve installed between the hot and cold line. During the charging process the water temperature inside the water heater might not reach the set temperature of 170°F since the controller is determining the charge as seen in Figure 6-6.

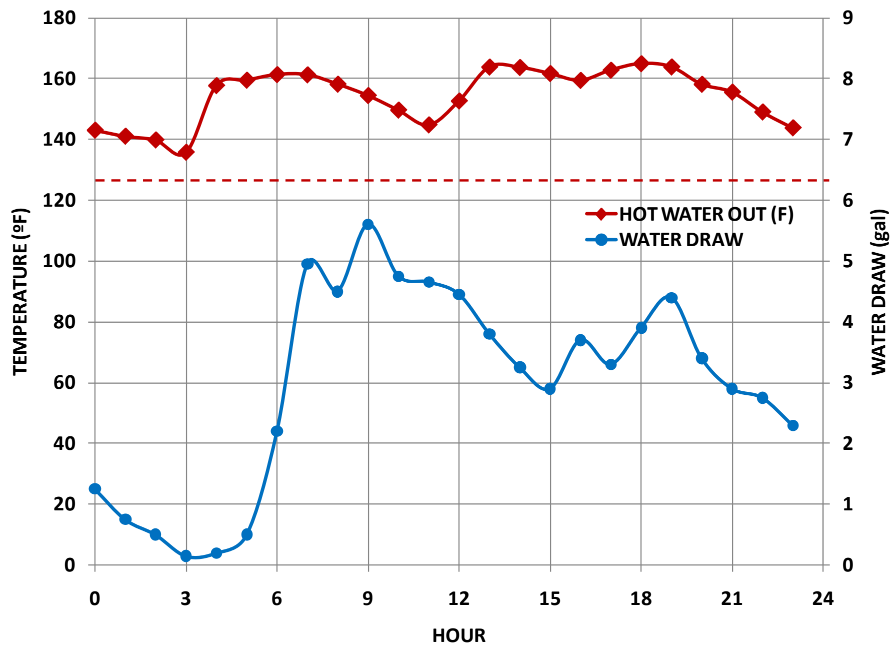


Figure 6-6
Hot Water Temperature and Water Draw for Optimizing LMP Strategy

Since both, the energy price and the energy consumed by the water heater are known; operating cost of the smart electric water heater can be calculated. The smart electric water heater in the optimizing LMP strategy uses 3773 kWh in a year. Assuming the LMP profile to be same everyday the operating cost of this smart electric water heater for the fixed water draw profile will be $62.50. It is important to note that this amount calculated based on the wholesale price of electricity and is not the retail price that a customer of such a water heater would pay. If the smart electric water heater was replaced by a regular water heater and the water draw profile and LMP values stay the same, the operating cost under these circumstances will be $165.

Utilities usually buy a small amount of energy in the real time market and the bulk of their energy on the day–ahead market to avoid the unpredictable nature of the real time markets and hence reduce risk. Figure 6-7 shows a comparison between the day ahead and real time price of energy. If the energy consumed by the smart electric water heater was bought on the day–ahead market, the smart electric water heater would cost $78.50 a year to operate. The lower operating cost of $62.50 in the real time market is due to the active monitoring of prices and the prices of energy at that particular day. This should not be considered as a general trend since the real time price curve is different every day. In the case of a regular water heater consuming energy bought on the day ahead market, the operating cost for a year would be $100 [Appendix B].

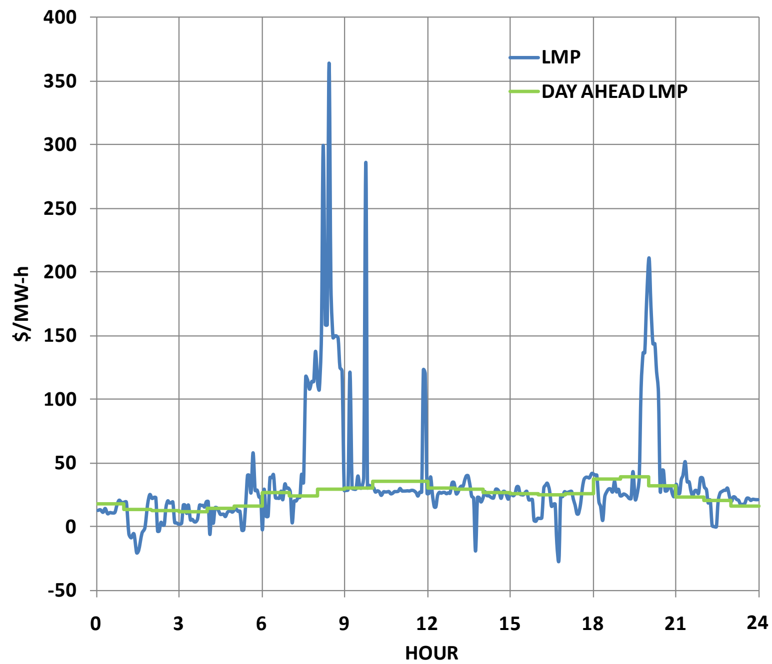


Figure 6-7
Comparison between Day-Ahead and Real-Time LMP

Regulation Strategy

A regulation strategy can be implemented in a smart electric water heater to provide frequency regulation in the energy marketplace. A water draw profile shown in Figure 6-1 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). This time of operation is offset by 2 hours to account for time zone between the server location (Dickinson, ND Mountain Time) and the test location (Knoxville, TN Eastern Time). This is not a limitation from the smart electric water heater manufacturer but is associated with the DAQ setup at EPRI. This should not affect the test results except for the shifted time of operation. PJM requires that the regulating resource must be electrically located within the PJM RTO territory. Although this condition is violated in this test setup, the concept remains true.

Implementing regulation strategy is more involved than the optimizing LMP strategy discussed in the previous section. 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.

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 in 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.

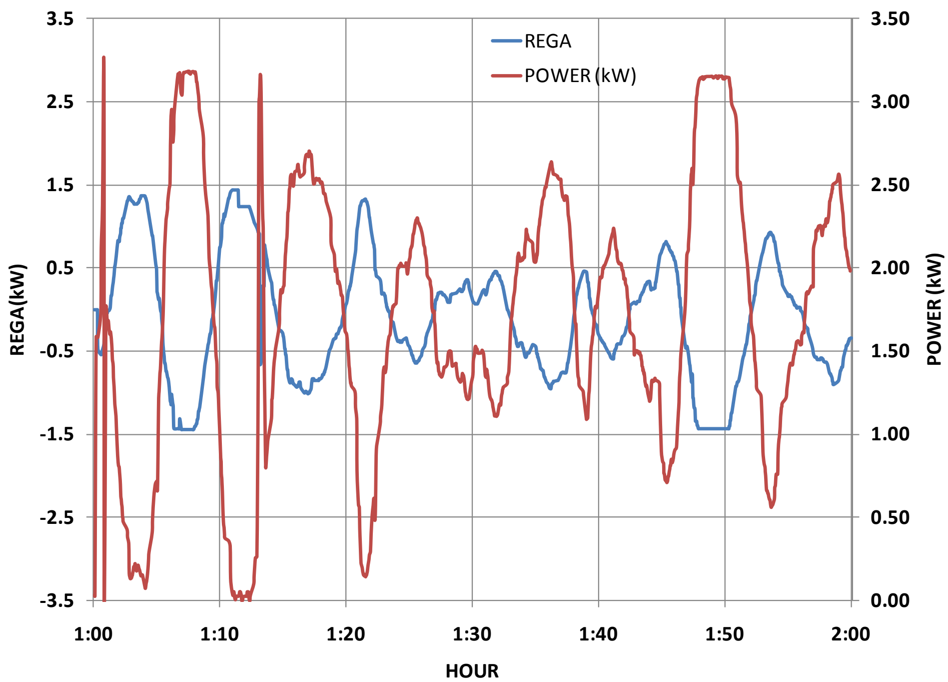


Figure 6-8
REGA Signal and Power Dissipated while Running Regulation Strategy

Figure 6-8 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. The overall power draw and energy consumption is shown in Figure 6-9. 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. The higher cost as compared to optimizing LMP strategy is because of running this strategy in the PJM area where the prices were high for the day under consideration. A detailed operating cost analysis is shown in Appendix C.

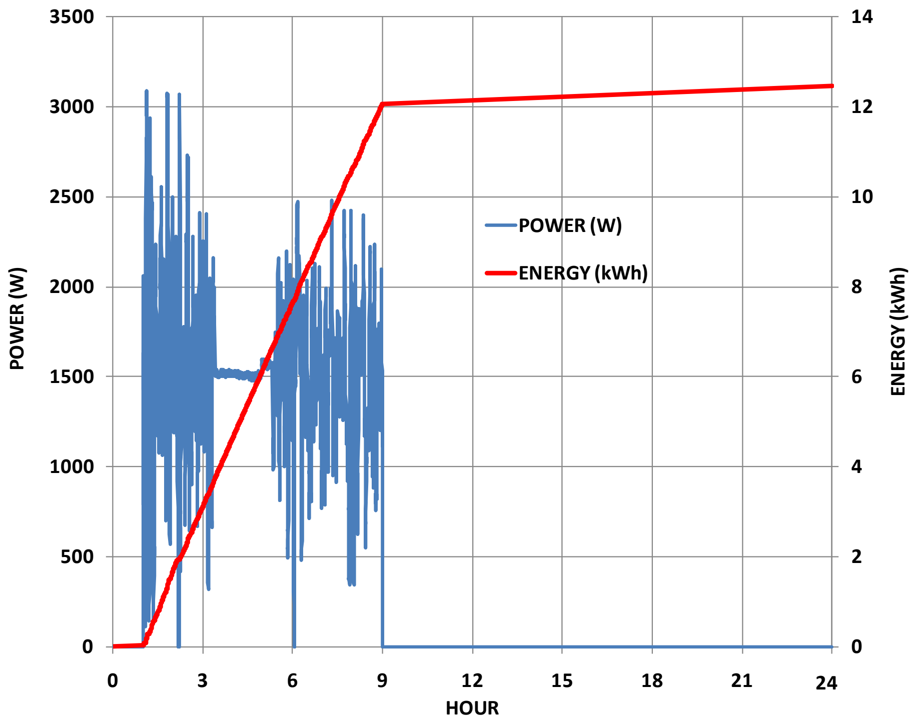


Figure 6-9
Total Power and Energy Consumption for Regulation Strategy

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. Figure 6-10 shows the RMCP and the DA-LMP values for a period of 24 hours. From Figure 6-9 any energy consumed above or below the baseline level of 1.5kWh for every hour counts as regulation provided. The REGA signal can be a positive value requiring the smart electric water heater to reduce the charge rate; the reduction in the charge rate is considered as regulation provided. 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 [Appendix C]. This benefit is dependent on the RMCP's and can vary depending on the grid conditions. At 3:00 am in Figure 6-10 the RMCP is greater than the DA-LMP which means that the smart electric water heater in this case is actually getting paid to use energy.

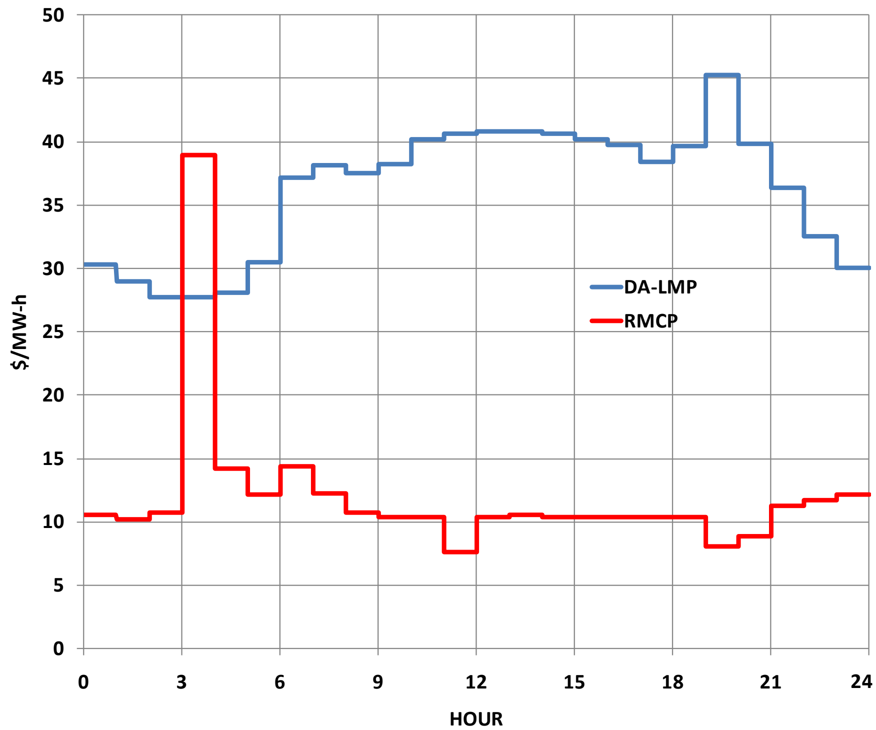


Figure 6-10
Day Ahead LMP and RMCP Values

The water draw profile and hot water temperature while running the regulation strategy is shown in Figure 6-11. The hot water temperature is consistently above 125ºF (except for at 1 am) while running this strategy.

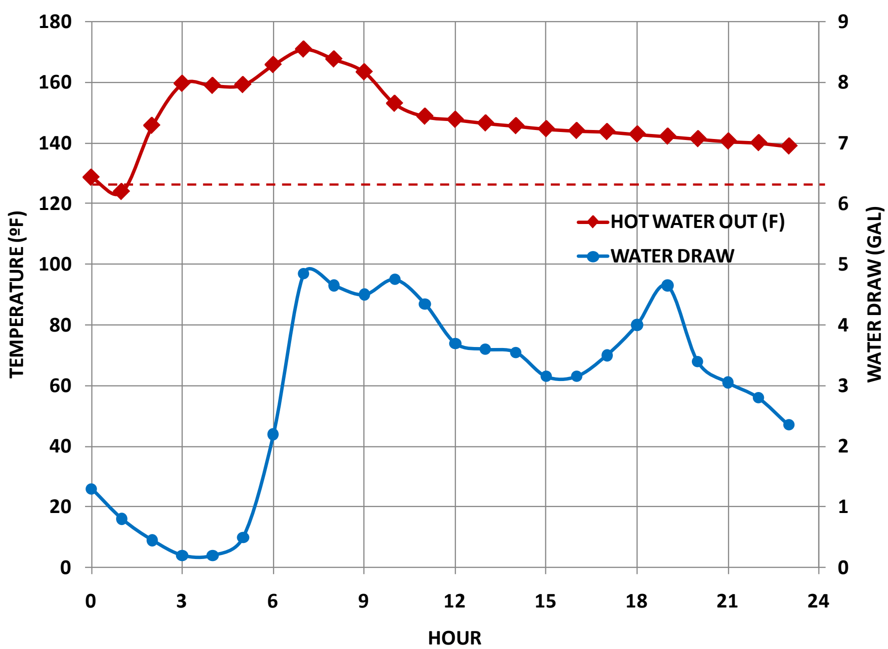


Figure 6-11
Hot Water Temperature and Water Draw for Regulation Strategy

Balancing Reserves Deployed Strategy

In the Balancing Reserves Deployed strategy the smart electric water heater follows the signal from BPA. The BRD signal is negative when decreased generation is required and positive when increased generation is required. The smart electric water heater follows this signal in a complimentary way – when the BRD signal is negative the water heater dissipates power.

Figure 6-12 shows the BRD signal and the power dissipated during the same time. It can be seen that the smart electric water heater charges only when the BRD signal is negative. The charging process is also a function of the residual charge level. The chart shows that the smart electric water heater started charging in the late afternoon hours when the BRD signal went negative. This can be explained by Figure 6-13. The charge level is a function of the water temperature and from Figure 6-13 it can be seen that the charge is decreasing during the afternoon time as hot water is drawn out of the water heater.

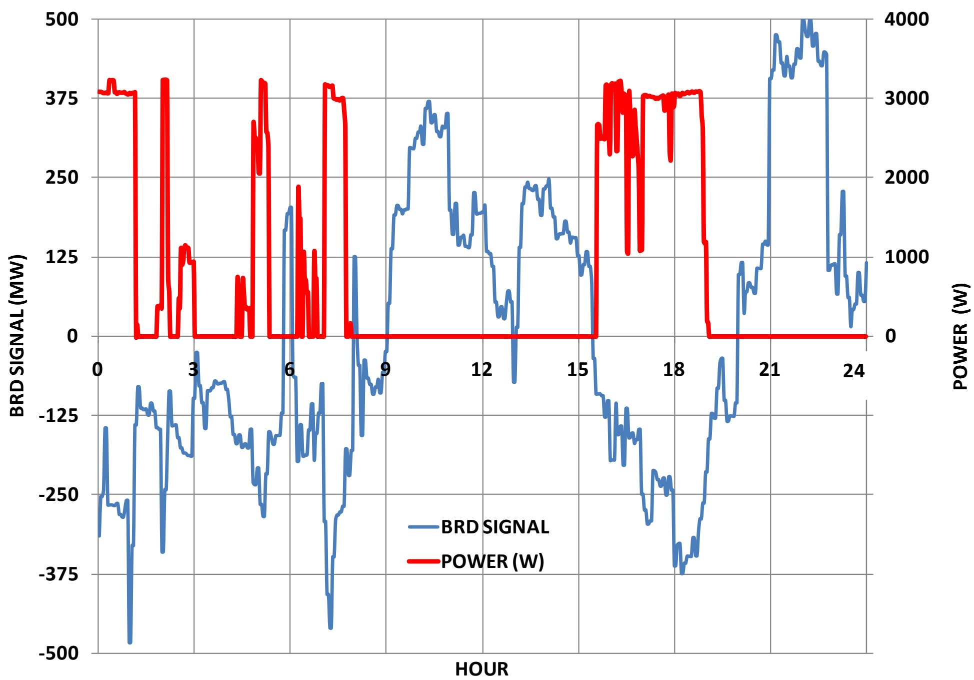


Figure 6-12
Balancing Reserves Deployed Signal from BPA

The smart electric water heater charging rate is also controlled based on the magnitude of negative value of the BRD signal. Figure 6-12 shows that the power dissipated is maximum when the BRD signal is below -250MW. There is a correction factor built into the algorithm to account for long- term positive BRD signal. This correction factor is necessary to keep the smart electric water heater charged if the BRD signals do not turn negative for extended period.

For the BRD following signal there is no financial incentive right now. The BRD signal is followed by the generators in BPA territory and they might have contracts with BPA but no contract exists between Steffes Corporation and BPA for providing this service.

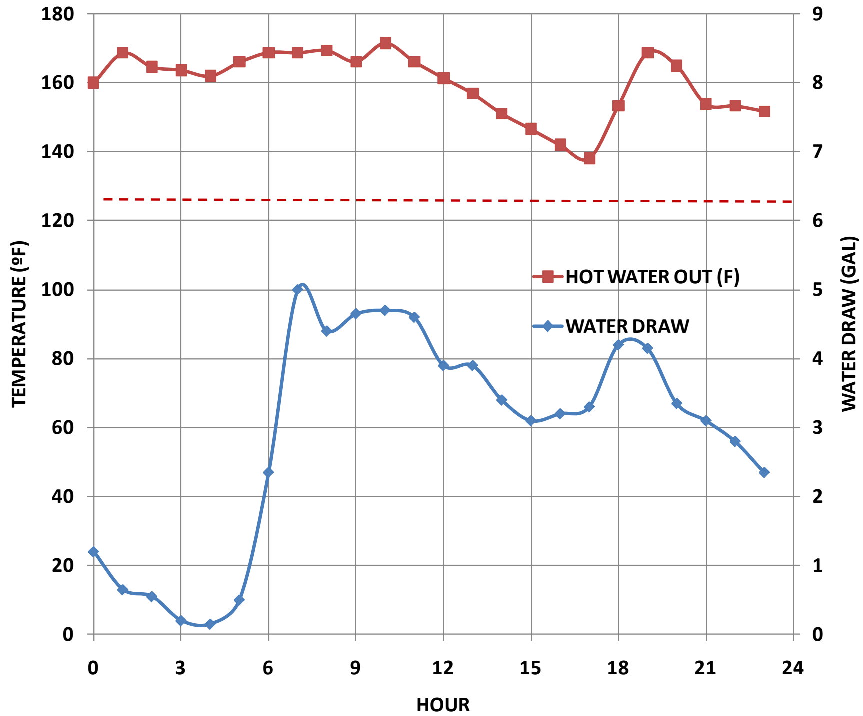


Figure 6-13
Hot Water Temperature and Water Draw for Follow BRD Signal Strategy

Summary of Test Results

Table 6-1 shows the operating cost per year for a regular water heater and a smart electric water heater. The regular water heater is always running uncontrolled. The difference in the energy cost per year is due the different days the strategies were tested which had different LMP's. Balancing Reserves Deployed signal following strategy has not been studied for energy cost per year but the strategy gives an overview of the capabilities of the smart electric water heater.

Table 6-1
Comparison of Wholesale Energy Cost/Year for Various Control Strategies

Type of Water Heater	Energy Cost ($/Year)		
	Uncontrolled	**Optimizing LMP**	**Regulation**
Regular Water Heater (Uncontrolled)	111.40	100	175
Smart Electric Water Heater		78.50	145.9

Test results show that the smart electric water heater is able to control the charging rate as well as charging duration to shift peak load. The hot water temperature in all strategies was always above 125ºF indicating that the smart electric water heater did not inconvenience the end user at any time.

7
CONCLUSIONS AND FUTURE WORK

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 peak load shifting capabilities of a smart electric water heater. 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 for identical conditions.

Opportunities for Utilities

Utilities can deploy smart electric water heaters in their service territory and implement various control strategies to control water heater load and even provide ancillary services depending on the wholesale markets they operate in. The strategies presented in this report can be modified to suit particular needs – for example the Optimizing LMP strategy can be simplified and used as a basic peak load shifting strategy. A 'Demand Response Energy Market' strategy can be implemented in the PJM territory where water heater load can be voluntarily reduced to receive payments based on day-ahead LMP for the qualified reductions.

The cost of storage in such a device is in the range of $30-$60 /kWh which is significantly less than any other comparable storage device. This low cost of storage and flexibility in utilizing the storage capabilities makes the smart electric water heater an ideal candidate for large scale deployment.

The smart electric water heaters can be marketed as thermal batteries that can be charged remotely. Projecting these smart electric water heaters as thermal batteries may also help manufacturers and utilities convince regulators to create exceptions when 10CFR 430.32 goes into effect. New business models may evolve with utilities providing rebates to purchase and install such water heaters. The business case will depend upon the strategy the utility might deploy. An aggressive control strategy like regulation strategy will make deeper discounts and rebates possible and help further adoption of this technology.

Challenges

Utilizing Smart electric water heater to store thermal energy has several challenges before it can become widely adopted.

Resistance Heating

Smart electric water heater relies on the resistance elements fast response to provide predictable and accurate response to various signals. 10CFR 430.32 requires electric water heaters above 55 gallon storage to have an energy factor of 2.057 which pushes electric resistance water heaters out of the market. Manufacturers are exploring avenues to allow an exception for the smart electric water heater so that resistance elements could be used.

Up Time

Up time is the time the smart electric water heater can actually be used as a peak load shifting or demand response device. Unlike other storage devices like batteries and flywheels, the up time for the smart electric water heater is the time when it's charging. Once the smart electric water heater is fully charged that particular smart electric water heater ceases to be a resource any more. Since the discharge rate is dependent on the water draw the smart electric water heater cannot be discharged by remote signals.

The up time of a single smart electric water heater is dependent on the water draw. If the water draw is low, the smart electric water heater will have a relatively low up time. For a smart electric water heater with a significantly higher water draw the up time will be high. Understanding the discharge pattern of a fleet of smart electric water heaters is necessary to optimize the combined up time.

Heavy users of hot water or occasional high use of hot water must be incorporated in the control strategies so that the charge time and hence the up time can be adjusted. For e.g.: operating water heater when LMP values are high might be necessary on certain occasions. In these situations the control strategy should be able to tweak itself.

Future Work

Field Tests

Tests in EPRI's Thermal Environmental Laboratory have demonstrated the peak load shifting capabilities of a smart electric water heater. The lab tests were conducted by subjecting one smart Electric Water Heater to a fixed water draw profile. Field tests with multiple units will be the logical next step in this work. Smart electric water heater subjected to real world use would provide valuable data to understand the peak load shifting capabilities. Field tests could also be used communications and customer satisfaction studies.

Modeling

The effect of thousands of such smart electric water heaters needs to be studied. Modeling efforts to supplement the lab and field data are necessary to predict the impact on the grid. Although it has been proved in lab tests that the smart electric water heater can be used to shift peak load, a detailed understanding of the exact nature of this demand side resource is necessary. Various newer strategies can be simulated within a model and current strategies can be tweaked to improve peak load shifting abilities as well as customer satisfaction.

8
ACRONYMS

ACE	Area Control Error
AGC	Automatic Generation Control
BRD	Balancing Reserves Deployed
BTU	British thermal unit
CAES	Compressed Air Energy Storage
CFR	Code of Federal Regulations
DA-LMP	Day ahead Locational Marginal Pricing
DAQ	Data Acquisition
DOE	Department of Energy
FERC	Federal Energy Regulatory Commission
GWh	Gigawatt hour
ISO	Independent System Operator
kW	kilowatt
kWh	kilowatt hour
LMP	Locational Marginal Pricing
LSE	Load Serving Entity
MISO	Midwest Independent System Operator
MJ	Mega Joule
MW	Megawatt
PJM	PJM Interconnection, a Regional Transmission Organization
PV	Photovoltaic
REGA	Fleet Regulation Signal
RMCP	Regulation Market Clearing Price
RPS	Renewable Portfolio Standards

RTO	Regional Transmission Organization
TREG	Total Regulation

9
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A
OPERATING COST OF REGULAR WATER HEATER

The operating costs of regular water heater and a smart electric water heater are calculated based on the actual wholesale energy price on the day a particular strategy was implemented. For example October 28^{th} 2011 is the day for which regular water heater data is analyzed. The operating cost for the regular water heater in this case is based on the day ahead LMP's for that particular day.

Water draw and energy consumption for a regular water heater is shown in Table A-1. The corresponding price of energy for October 28^{th} in the MISO System is shown in

Table A-1
Water Draw and Energy Consumed in Regular Water Heater

HOUR	WATER DRAW (GAL)	ENERGY CONSUMED (kWh)
1	1.3	0.178162
2	0.75	0.157104
3	0.5	0.119812
4	0.2	0
5	0.2	0.065186
6	0.45	0.078064
7	2.25	0.277527
8	4.9	0.544067
9	4.7	0.561706
10	4.85	0.555726
11	4.8	0.571716
12	3.95	1.808594
13	4.25	0.403137
14	3.9	0.343567
15	3	0.310913
16	3.15	0.304382
17	3.45	0.328674
18	3.1	0.358582
19	3.95	0.442444
20	4.05	0.506531
21	3.3	0.441162
22	3	0.41571

HOUR	WATER DRAW (GAL)	ENERGY CONSUMED (kWh)
23	2.7	0.311707
24	2.3	0.28

The product of energy consumed in Table A-1and the DA-LMP from Table A-2 gives the cost to operate the water heater every hour. Sum of all the operating hours in the day is the total cost per day. The price of electricity was assumed to be constant for all year (same hourly rates as in Table A-2). Multiplying the cost per day by number of days in year provides the operating cost per year which in this case came out to be $111.40.

Table A-2
Day Ahead LMP's from MISO System for October 28th 2011

HOUR	DA-LMP
1	22.64
2	21.86
3	21.65
4	21.67
5	22.81
6	29.21
7	36.94
8	38.43
9	38.62
10	37.67
11	37.41
12	33.51
13	29.95
14	28.47
15	26.88
16	26.36
17	26.06
18	29.03
19	39.43
20	38.69
21	31.93
22	29.87
23	25.94
24	24.29

B

OPERATING COST FOR OPTIMIZING LMP STRATEGY

For the optimizing LMP strategy, the baseline test is not run again. Instead energy consumed values from Table A-1 are used with the DA-LMP's for the appropriate day, in this case October 13th, 2011 shown in Table B-1.

Table B-1
Day Ahead LMP's from MISO

HOUR	DA-LMP
1	18
2	13.77
3	12.68
4	12.04
5	14.13
6	16.26
7	26.45
8	24.4
9	29.39
10	30.27
11	35.97
12	35.38
13	30.69
14	29.22
15	26.87
16	26.25
17	24.65
18	26.2
19	37.55
20	38.78
21	32.18
22	23.28
23	20.22
24	16.64

Following the same procedure as used in the regular water heater strategy, the yearly operating cost considering the wholesale price of electricity is $100.3. This will be the baseline cost for the day under consideration - October 13th 2011. With the optimized LMP strategy the energy use is modified and is shown in Table B-2.

Table B-2
Water Draw and Energy Consumed while Running Optimized LMP Strategy

HOUR	WATER DRAW (GAL)	ENERGY CONSUMED (kWh)
1	1.25	0.00119
2	0.75	1.808686
3	0.5	1.67157
4	0.15	1.490234
5	0.2	0.031647
6	0.5	0
7	2.2	0
8	4.95	0
9	4.5	0
10	5.6	0
11	4.75	0
12	4.65	0.786071
13	4.45	0.867005
14	3.8	0.62381
15	3.25	0.739838
16	2.9	0.649353
17	3.7	0.754913
18	3.3	0.48526
19	3.9	0.07074
20	4.4	0
21	3.4	0
22	2.9	0
23	2.75	0.35559
24	2.3	0

The product of energy consumption from Table B-2 and the prices in Table B-1 result in a daily operating cost of $0.21 and a yearly operating cost of $78.50.

C
OPERATING COST FOR REGULATION STRATEGY

For regulation strategy the market values from October 6th 2011 (PJM) are used. For comparing regulation strategy to the baseline standard water heater, the same water draw and energy consumption from Table A-1 is assumed. The DA-LMP prices for October 6th 2011 are shown in Table C-1.

Table C-1
Day Ahead LMP's from PJM for Regulation Case

HOUR	DA-LMP
1	30.27
2	29.00
3	27.73
4	27.72
5	28.13
6	30.46
7	37.19
8	38.17
9	37.54
10	38.22
11	40.20
12	40.61
13	40.81
14	40.79
15	40.67
16	40.23
17	39.75
18	38.41
19	39.67
20	45.26
21	39.86
22	36.33
23	32.53
24	30.05

At these prices and energy consumption defined in Table A-1 regular water heater will cost $0.36 per day or $131.80 per year. The energy use is modified using the regulation strategy as shown in Table C-2.

Table C-2
Water Draw and Energy Consumed while Running Regulation LMP Strategy

HOUR	WATER DRAW (GAL)	ENERGY CONSUMED (kWh)
1	1.3	0.03
2	0.8	1.65
3	0.45	1.42
4	0.2	1.53
5	0.2	1.51
6	0.5	1.49
7	2.2	1.48
8	4.85	1.5
9	4.65	1.425
10	4.5	0.03
11	4.75	0.02
12	4.35	0.03
13	3.7	0.02
14	3.6	0.02
15	3.55	0.03
16	3.15	0.02
17	3.15	0.03
18	3.5	0.03
19	4	0.02
20	4.65	0.03
21	3.4	0.03
22	3.05	0.03
23	2.8	0.03
24	2.35	0.03

The product of energy consumption from Table C-2 and the prices in Table C-1 result in a daily operating cost of $0.40 and a yearly operating cost of $145.9. Although the operating cost looks higher for the regulation strategy it should be noted that the energy input using the regulation strategy is higher than the energy input for a regular water heater. The excess energy used in regulation strategy is a result of storage capacity that exists in the water heater. Since the analysis is done for one day, this particular day the smart water heater charged to a higher charge level.

The following day the energy usage will be less since the smart water heater has to discharge before it can store any further charge. To make a valid comparison between cost to operate regular and smart electric water heater, cost to operate regular water heater at higher energy consumption is calculated by taking ratio of energy used in both cases. Once adjusted for the energy usage the regular water heater costs $0.47 to operate per day or $175 per year.

The payout for regulation service provided is calculated in Table C-3. Since the regulation capacity offered in the market was 1.5 kWh per hour for eight hours, the total regulation capacity is 12 kWh. The product of regulation capacity offered each hour and the RMCP for that corresponding hour yields the payout for given hour.

Table C-3
Regulation Service Payout Calculations

HOUR	REGULATION CAPACITY OFFERED (kWh)	RMCP ($/MWh)	PAYOUT $
1	1.5	10.22	0.015
2	1.5	10.71	0.016
3	1.5	38.93	0.058
4	1.5	14.22	0.021
5	1.5	12.17	0.018
6	1.5	14.35	0.026
7	1.5	12.23	0.018
8	1.5	10.77	0.016

The total payout for one day of regulation service is sum of payout for all hours which in this case is $0.185.

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