The Hidden Battery

Opportunities in Electric Water Heating

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Executive Summary

While conventional water heating load control and energy efficiency programs have been offered in the U.S. for decades, new developments have led to the rediscovery of water heaters as an attractive opportunity for improving the reliability, economics, and environmental footprint of the power grid. In particular, the growing adoption of intermittent sources of generation, such as wind and solar, is leading utilities, power system operators, and regulators to explore new ways to reliably and cost-effectively integrate renewables onto the power system. "Flexible load" in the form of demand response or behind-the-meter energy storage is frequently discussed as a possible solution.

Electric water heaters are essentially pre-installed thermal batteries that are sitting idle in more than 50 million homes across the U.S.[1] By heating the water in the tank to store thermal energy, water heaters can be controlled in real-time to shift electricity consumption from higher-priced hours when less efficient generating units are operating on the margin to lower-priced hours when less costly generation is operating on the margin and, in some cases, there may be excess supply of energy from low- or zero-emitting resources such as wind power. Further, recent technological advancements have enabled "grid interactive water heaters" to be controlled over very short time intervals and with near instantaneous response, allowing them to provide frequency regulation and other grid balancing services that are highly valuable in markets with rapid fluctuations in supply.

In addition, a policy focus on clean energy is driving interest in energy efficiency improvements. A new federal energy efficiency standard for large electric water heaters, combined with subsequent legislation that allows for the manufacture of grid-enabled electric resistance water heaters, has created a significant opportunity for reductions in both cost and emissions from a large source of residential energy consumption.[2]

The magnitude of this relatively untapped resource is significant. Electric water heaters account for 9% of all electricity consumed by households nationally. This represents the third single largest source of residential electricity consumption, behind only space cooling (13%) and lighting (11%).[3] More than 40 percent of U.S. households have electric water heating.[4]

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[1] See U.S. Census Bureau (2013).

[2] In 2010, the U.S. Department of Energy (DOE) established an energy efficiency standard that would effectively require all new residential electric water heaters above 55 gallons to be heat pump water heaters, beginning April 2015. Congress subsequently passed the Energy Efficiency Improvement Act of 2015, which includes an exception to this rule for high-efficiency 75+ gallon electric resistance water heaters that are "grid-enabled" and intended for participation in a demand response program.

[3] See EIA (2015).

[4] See U.S. Census Bureau (2013).

In light of these opportunities, the purpose of this study is to analyze the economics of a range of advanced electric water heating load control and energy efficiency strategies that utilities and demand response aggregators could implement to reduce total system costs.

We consider two types of electric water heating technologies: electric resistance water heaters (ERWHs), which use an electric heating element to directly heat water and maintain a desired temperature by turning on and off in short “bursts” of energy; and heat pump water heaters (HPWHs) which draw heat from the surrounding air to heat the water. The heat pump water heaters typically use electricity at a low and steady state, though a “hybrid” form of HPWHs also has an electric heating element which can provide additional heating capability when needed.

We evaluate the economics of several different strategies for controlling the load of these water heaters. The strategies include conventional “peak shaving” in which load is curtailed during peak hours on a limited number of days per year, “thermal storage” in which the water is heated each night to avoid higher priced hours during the day, and a “fast response” strategy that would provide balancing services in the form of quick load increases and decreases. Drawing upon detailed simulations of water heater operations and with consideration for different market structures, we assess the economic and environmental impacts of five water heating strategies for two different water tank sizes and three distinctly different market scenarios.

Advanced electric water heating strategies, such as providing ancillary services, storing thermal energy on a daily basis, or adopting heat pumps, can provide significant value. We find that, in some cases, the net benefits of these approaches could reach around $200 per participant per year under certain market conditions. This would effectively pay for the entire cost of the water heater and associated control equipment (including installation) in 5 years. Considering only incremental costs of the advanced control capability, the payback period is around 3 years. Both HPWHs and controlled ERWHs can have very strong positive economics, depending on market conditions. Controlled ERWHs provide the largest economic benefit on a per-water heater basis under the market scenarios analyzed in this study. Figure ES-1 shows the estimated incremental annualized net benefits of each of the water heating strategies analyzed in this study, based on market prices observed in PJM in 2014.[5] These net benefits are incremental relative to maintaining an uncontrolled 50-gal ERWH (the baseline assumption).

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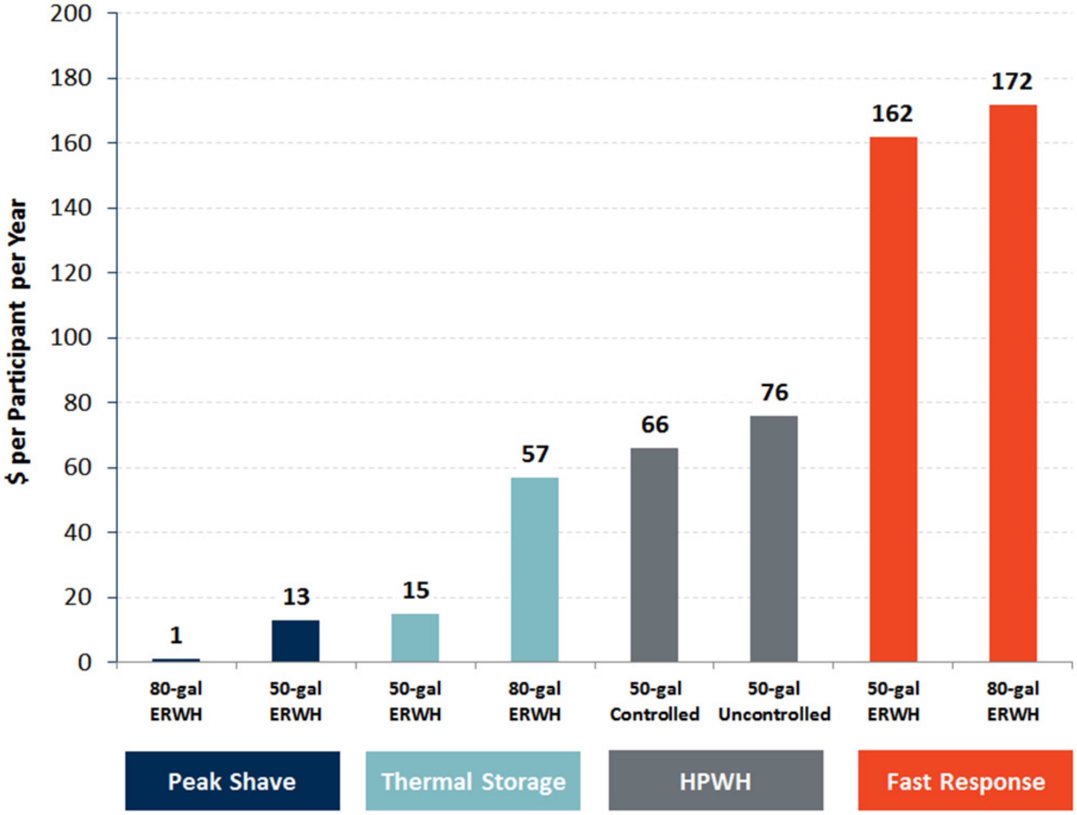
[5] The figure shows benefits associated with a single incremental water heater. The analysis does not account for the dynamic impact that participation in large quantities may have on market prices; this is an important area for further research.

Figure ES-1: Annualized Net Benefits of Water Heating Strategies (PJM 2014)



The environmental impacts of ERWHs depend heavily on the water heating control strategy being considered and the composition of the generation supply mix of the power system. Generally, HPWHs provide the most consistent environmental benefit on a per-water heater basis through overall reductions in energy consumption, reducing CO_2 emissions by approximately 50% relative to an uncontrolled ERWH in our analysis.[6] The environmental case for controlled ERWHs is more nuanced, but also appears to have significant potential due to a combination of strong economics and modest direct emissions impacts.

Figure ES-2 illustrates the CO_2 emissions impact of two of the water heating strategies - an 80-gallon ERWH curtailed on a daily basis to provide thermal energy storage, and a 50-gallon uncontrolled HWPH. The emissions impact was estimated for two markets with a different assumed generation supply mix - one with coal and gas as the marginal supply and the second with gas renewables as the marginal supply. In the market scenario with coal and gas on the margin, we considered a case when the ERWH is curtailed purely for economic reasons (i.e., to

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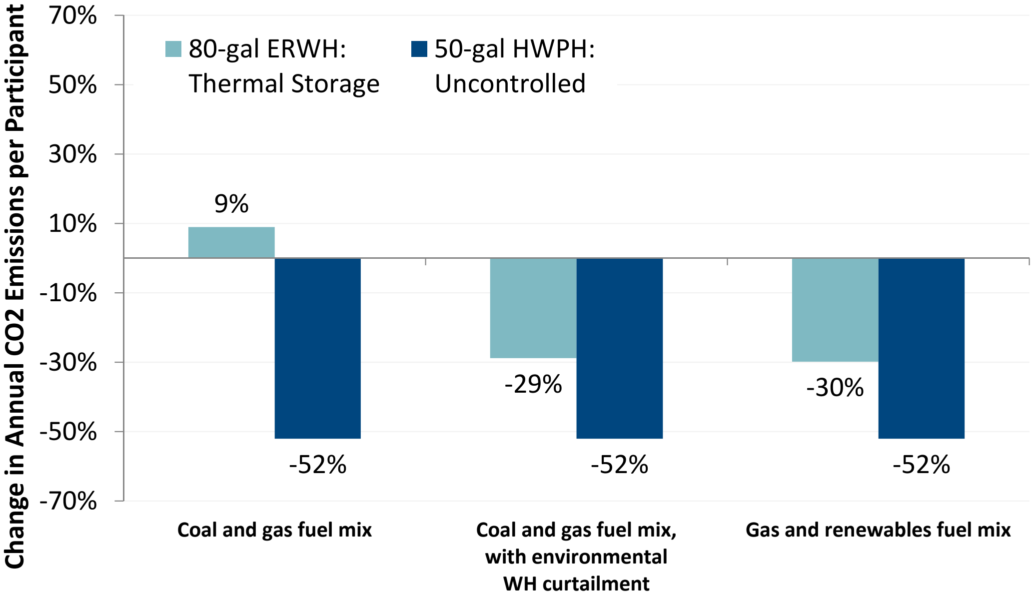
[6] Note that the efficiency gains of HPWHs are heavily dependent on the temperature of the surrounding air, making them better suited for warmer rather than colder environments. Therefore, the potential benefits of HPWHs can vary significantly across regions and climates.

maximize energy, capacity and ancillary services cost savings) and a case when it is curtailed to shift load away from hours with higher emissions.

Figure ES-2: Change in Water Heater CO_2 Emissions (Relative to Baseline Uncontrolled 50-gallon ERWH)



Notes:
Figure shows only two of many possible different marginal fuel mix scenarios; results can vary significantly based on the assumed fuel mix and water heater load curtailment or efficiency strategy. Coal/gas scenario based on 2014 PJM market conditions. Gas/renewables scenario based on illustrative assumptions. Environmental water heater curtailment based on reasonable but illustrative assumptions about water heater operations. Emissions of 50-gal tanks are lower than those of 80-gal tanks due to different efficiency levels. Efficiency benefit of HPWHs depends heavily on ambient air temperature. Total annual marginal CO2 emissions of baseline uncontrolled 50-gallon ERWH are 1.9 tons in the coal/gas scenario and 0.5 tons in the gas/renewables scenario.

The emerging load control and efficiency strategies are complementary to established options that have been in practice for decades, such as peak load shaving. The benefits of all of these strategies may be best maximized through a portfolio-based offering rather than promoting only one single technology type, particularly as the capabilities of the technology continue to evolve and the industry gains experience with these options. Specific observations about each water heating strategy include:

- The Peak Shave strategy is well suited for market conditions in which there is a peak demand-driven need for generation and/or transmission capacity, a relatively flat energy price profile, and/or a limited ability to promote adoption of larger ERWH tank sizes.

- The Thermal Storage strategy can significantly increase benefits relative to the Peak Shave strategy, at little incremental cost, if offered to customers with larger (80+ gallon) water tanks in market conditions with a significant price differential between peak and off-peak periods.

- The Fast Response strategy can significantly increase benefits over the other two load control strategies in markets with a need for resources that can quickly ramp load up and down. Ancillary services benefits are less dependent on tank size but very dependent on market conditions, including whether market rules allow demand-side resources to participate in ancillary services markets.

- Uncontrolled heat pump water heaters provide significant economic and environmental benefits in those locations where often-challenging technical factors can be effectively addressed.

While the findings in this study are robust across a diverse range of market scenarios, they certainly depend on regional market conditions. A detailed economic analysis should be conducted in any market where a new program is being considered. Moving forward, there are a variety of new initiatives that would extend the findings of this study and further enhance the industry's understanding of emerging opportunities in electric water heating. These include:

- **Assess techniques for optimal management and dispatch of a portfolio of water heaters.** This could include optimized dispatch of an individual water heater across the various value streams (energy, capacity, ancillary services, and environmental impacts). It could also include analysis of a "community storage" approach to water heating load control which would coordinate the dispatch across a portfolio of water heaters to maximize the value of the program to the grid. It could also include location-specific dispatch of the water heaters and other sources of load to increase distribution system benefits, an issue that is being explored currently through initiatives in New York, California, and Hawaii, among other jurisdictions.

- **Analyze participant benefits.** In addition to the system/societal costs and benefits analyzed in this study, analysis of the bill savings to participants and non-participants would provide insight regarding the customer-facing policies and incentive structures that could be used to facilitate economic participation in the programs.

- **Analyze the impact of varying levels of adoption of the water heating strategies on wholesale electricity market prices.** Particularly as it relates to ancillary services, large levels of adoption of water heaters used as storage on the electricity grid could have a significant impact on the wholesale electricity market prices, so accounting for the "depth" of the market would be an informative extension of this study.

- **Extend the analysis to other market settings.** This analysis focused on benefits in the PJM and MISO markets. Expanding to additional markets with different market rules, such as ERCOT, CAISO, or international markets, for example, would provide further insight as to the performance of the strategies across a range of market conditions.

I. Introduction

While conventional water heating load control and energy efficiency programs have been offered in the U.S. for decades, new developments have led to the rediscovery of water heaters as an attractive opportunity for improving the reliability, economics and environmental footprint of the power grid. In particular, growing adoption of intermittent sources of generation, such as wind and solar, is leading utilities, power system operators, and regulators to explore new ways to reliably and cost-effectively integrate renewables into the power system. "Flexible load" in the form of demand response or behind-the-meter energy storage is frequently discussed as a possible solution.

Electric water heaters are essentially pre-installed batteries that are sitting idle in more than 50 million homes across the U.S.[7] By heating the water in the tank to store thermal energy, water heaters can be controlled in real-time to shift electricity consumption from higher-priced hours when less efficient generating units are on the margin to lower-priced hours when, in some cases, there may be excess supply of energy from renewables. Further, recent technological advancements have enabled "grid interactive water heaters" to be controlled over very short time intervals and with near instantaneous response, allowing them to provide frequency regulation and other balancing services that are highly valuable in markets with rapid fluctuations in supply.

The magnitude of this resource is significant. Water heating is the third largest source of residential electricity use in the U.S., accounting for 9% of all household electricity consumption.[8] This represents the third single largest source of residential electricity consumption, behind only space cooling (13%) and lighting (11%).[9] More than 40 percent of U.S. households have electric water heating.[10] For a typical customer with an electric resistance water heater, 15% to 30% of their annual electricity bill might be attributable to water heating alone.[11]

At the same time, a policy focus on clean energy is driving interest in energy efficiency improvements. A new federal energy efficiency standard for large electric water heaters, combined with subsequent legislation that allows for the manufacture of grid-enabled electric

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[7] See U.S. Census Bureau (2013).

[8] See EIA (2015).

[9] See EIA (2015).

[10] See U.S. Census Bureau (2013).

[11] For example, a customer with total average monthly electricity consumption of 1,200 kWh, monthly water heating electricity consumption of 350 kWh, and a flat and largely volumetric retail rate would spend approximately 30% of their electricity bill on water heating.

resistance water heaters, has created a significant opportunity for reductions in both cost and emissions from a large source of residential energy consumption.[12]

The operational viability of the technology is being proven in the market. Demonstration projects in Hawaii and Minnesota, for example, have shown that water heaters can quickly respond to real-time control signals.[13] The Sacramento Municipal utility District (SMUD) has equipped some customers with 20-gallon electric resistance water heaters that are additional to their existing gas or electric water heater. The utility effectively operates the second water heater as a behind-the-meter battery, while at the same time providing the customers with the benefit of an additional source of water heating capacity.[14] New, intelligent algorithms are being explored to take advantage of water temperature differentials in the top and bottom of the tank and minimize risk of hot water shortages for customers,[15] and new protocols are being developed to standardize communications with the water heaters.[16]

Research on advanced water heating opportunities is beginning to emerge as well. For example, water heating load control was included in a recent national assessment of the economics of a portfolio of flexible load options.[17] Water heating load control has been identified as one option for addressing the renewables integration challenges associated with the California ISO's "Duck Curve."[18] And some water heating technology manufacturers have published studies on the economic and environmental benefits of flexible water heating load.[19] While this research addresses a range of important issues, there is a growing need to better understand the comparative benefits and costs of different electric water heating technologies under a range of market conditions.

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[12] In 2010, the U.S. Department of Energy (DOE) established an energy efficiency standard that would effectively require all new residential electric water heaters above 55 gallons to be heat pump water heaters, beginning April 2015. Congress subsequently passed the Energy Efficiency Improvement Act of 2015, which includes an exception to this rule for high-efficiency 75+ gallon electric resistance water heaters that are "grid-enabled" and intended for participation in a demand response program.

[13] See Podorson (2014).

[14] See Rasin (2015)

[15] See St. John (2013).

[16] See EPRI (2014).

[17] The Rocky Mountain Institute recently explored the economics of flexible load, including electric water heating, in its reported titled "The Economics of Demand Flexibility." See Dyson et al. (2015).

[18] See Lazar (2014).

[19] See Steffes.

In light of these developments, the purpose of this study is to analyze the economics of a range of advanced electric water heating load control and energy efficiency strategies that utilities and demand response aggregators might implement to reduce total system costs. We establish a general methodological framework for evaluating the economics of several different water heating load control and efficiency strategies. Drawing upon detailed simulations of water heater operations and with consideration for different wholesale market conditions, we assess the economic and environmental impacts of five water heating strategies for two different water tank sizes and three distinctly different market scenarios.

The remainder of this report is organized as follows. Section 2 discusses the methodological framework. Section 3 summarizes the costs and benefits of each of the water heating strategies at the individual customer level, as well as the impact of the water heating strategies on CO_2 emissions and the potential impacts of a portfolio of water heating strategies at the aggregate system level. Section 4 presents conclusions and recommendations. The appendices include additional detailed information about assumptions, methodology, and results.

II. Methodology

We consider two types of electric water heating technologies in this study. Electric resistance water heaters (ERWHs) use an electric heating element to directly heat water, maintaining a desired temperature by turning the element on and off in short "bursts" of energy. Heat pump water heaters (HPWHs), on the other hand, draw heat from the surrounding air to heat the water. They typically use electricity at a low and steady state, though all current HPWH models are "hybrids" with an electric heating element which can provide additional heating capability when needed.

Consider a residential utility customer who needs to replace an old 50-gallon ERWH. Through programmatic offerings, the utility could offer this customer a range of choices that require him or her to make some important decisions. For instance, should the customer install another ERWH, or instead install a more efficient HPWH? Should the customer enroll in a water heating demand response (DR) program, which would allow the water heating load to be controlled by the utility in return for financial compensation? Should the customer purchase a larger water tank, which could increase hot water storage capability?

The utility could encourage customers to pursue combinations of these choices by offering financial incentives, each of which would constitute a different possible "strategy." For instance, the utility could offer incentives for customers to purchase a larger ERWH and participate in a DR program. This would give the utility access to significant thermal energy storage capacity, which could be used to modify the customer's electricity consumption pattern in a way that is beneficial to the power system. Or the utility could offer rebates for the purchase of a HPWH, which would lead to an overall reduction in the customer's electricity consumption and an improvement in overall energy efficiency.

In this study, we analyze the system costs and benefits (also commonly referred to as "societal" costs and benefits) of several water heating strategies. The costs and benefits of each strategy are estimated relative to a baseline scenario in which the customer simply replaces their old water heater with another uncontrolled 50-gallon ERWH. The strategies analyzed include several different DR program options in which the customer could enroll. The benefits and costs of the strategies are analyzed under a range of different market conditions.

THE BASELINE

Each of the water heating strategies is compared to a baseline case that is represented by a 50-gallon uncontrolled ERWH. A 50-gallon water heater is used as the baseline because the most common size of water heaters in the U.S. is in the 40- to 50-gallon range.[20] The baseline ERWH's

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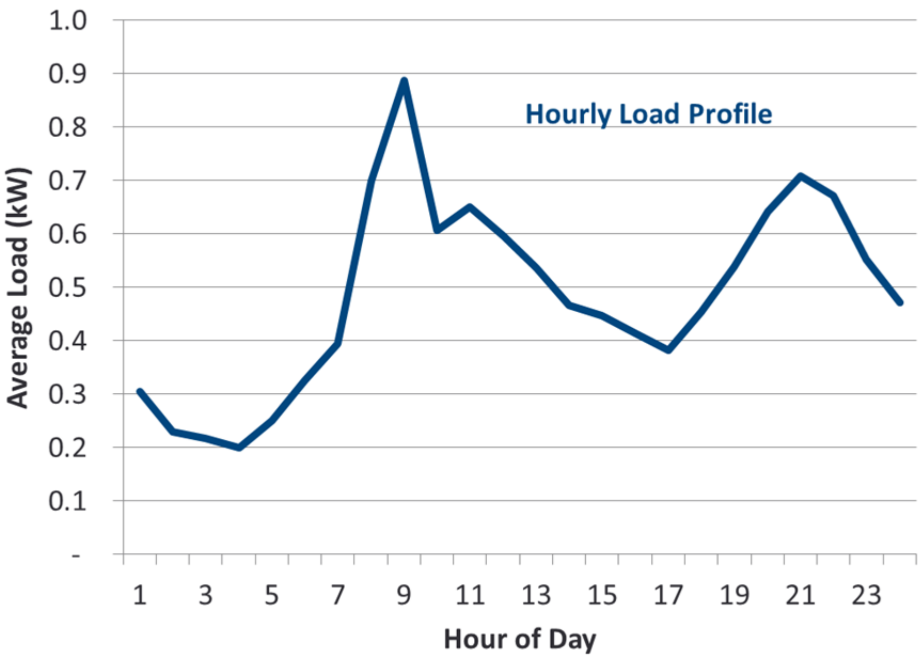
[20] According to the 2009 EIA Residential Energy Consumption Survey, more than half of all residential water heaters in the U.S. are between 30 and 50 gallons, see EIA (2009).

efficiency level in our study is modeled to be consistent with DOE minimum standards as of April 2015.[21] The daily load profile of the baseline water heater is based on an average of individual residential consumption patterns in Great River Energy's (GRE's) Minnesota service territory. This load profile is assumed to maintain a water temperature of at least 120 degrees, which is the standard temperature to which water is heated in most residential applications. Figure 1 summarizes the hourly load profile.

Figure 1: Average Electricity Usage Profile of Baseline 50-gallon ERWH



THE WATER HEATING STRATEGIES

Three ways of using the water heater as a demand response resource were analyzed for ERWHs. The strategies were analyzed for both 50- and 80-gallon water heaters, to explore the economic impacts of increasing the storage capability of the water heater. The three strategies are:

Strategy #1: Peak Shave. In the Peak Shave strategy, the water heater is curtailed only on a limited number of days of the year (typically 10 to 15) when the system peak is likely to occur. Curtailments occur for a limited number of hours on those days (typically 2 to 4, depending on

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[21] As of April 16, 2015 ERWHs between 20 and 55 gallons must have an energy factor as defined by the equation: Energy Factor = 0.960 – (0.0003 x Rated Storage Volume in gallons); tanks with a rated storage volume above 55 gallons must have an energy factor of: EF = 2.057 – (0.00113 x rated storage volume in gallons). Grid interactive ERWHs larger than 55 gallons must have an energy factor of: EF = 1.061 – (0.00168 x rated storage volume in gallons). See DOE (2015).

the duration needed to confidently capture the hour of the system peak). The water heater is not controlled on the other days of the year. This strategy is used largely to capture capacity value.

Strategy #2: Thermal Storage. With the Thermal Storage strategy, on a daily basis the water heater heats at night and then is curtailed during highest priced hours of day. The total number of hours curtailed during the day depends on the size of the tank and the amount of hot water it can store. Larger tanks can store more hot water and therefore be curtailed for more hours during the day without risking hot water shortages. The thermal storage strategy is used to capture energy value through energy price arbitrage and capacity value discussed in Strategy #1. Since load is being curtailed during the peak daytime hours, we assume that the strategy would also include curtailment of the water heater to provide capacity value, in addition to the energy value.

Strategy #3: Fast Response. With the Fast Response strategy, the water heater offers frequency regulation into the wholesale ancillary services market while heating water during off-peak hours, on a daily basis. The water heater responds to a signal from the system operator and in a matter of seconds can increase or decrease load depending on the need. For the purposes of this study, we have analyzed the provision of frequency regulation consistent with the requirements of PJM's Dynamic Regulation ("RegD") market.[22] As it is estimated in our analysis, we also assume that the water heater is controlled to capture additional energy and capacity value, although the dispatch heuristic is not perfectly optimized across these three value streams.

Of the three ERWH strategies, the Peak Shave and Thermal Storage strategies have been successfully employed by utilities on a full-scale basis for many years. The Fast Response strategy has emerged more recently, as the technology necessary to offer ancillary services from water heaters has achieved commercial availability only in the past year or two. Several pilot projects have demonstrated the ability of water heaters to provide frequency regulation. For example, in Minnesota, Great River Energy equipped 10 water heaters with Steffes Water Heater Controllers and followed a simulated control signal.[23] The EPRI Grid-Connected Water Heater Demonstration Project equipped an 85-gallon ERWH with a Steffes controller and successfully followed a MISO regulation signal.[24] The Pacific Northwest National Laboratory (PNNL) also tested the ability of water heaters to follow a simulated control signal in PJM.[25] A pilot demonstration project by the Hawaiian Electric Company equipped 49 80-gallon water heaters with Sequentric controllers and followed regulation control signals.[26] Additional projects are underway in other parts of the country and the technology is developing rapidly.

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[22] See PJM (2013).

[23] See NRECA (2014).

[24] See NRECA (2015).

[25] See PNNL (2015).

[26] See Battelle (2015).

In analyzing the Fast Response strategy, we assume that market structures are in place to enable the participation of distributed storage in the frequency regulation market. To provide frequency regulation, resources must be able to respond in a matter of seconds. Frequency regulation prices tend to be higher than other ancillary services, as only a subset of fast-ramping resources are capable of providing the service.

We have estimated the benefits of the Fast Response strategy in both PJM and MISO markets. PJM currently enables the participation of storage in the frequency regulation market through the "RegD" frequency response signal. This signal is designed to ensure storage devices provide Reg-Up (i.e., fast load reductions) half of the time and Reg-Down (i.e. fast load increases) half of the time, remaining energy neutral over the course of an hour. In MISO, to account for the potential value of this service, we estimated frequency regulation value using historical MISO regulation prices and assuming behind-the-meter resources can provide frequency regulation, although no such policy for behind-the-meter participation currently exists to our knowledge.[27]

Both MISO and PJM do not have separate markets for Reg-Up and Reg-Down. A resource therefore must be able to provide equal amounts of both Reg-Up and Reg-Down. A water heater can provide Reg-Up by reducing demand, and Reg-Down by increasing demand. Therefore, we estimated the amount of frequency regulation a water heater can provide as set by its hourly average electricity demand and assumed that the water heater can reduce its electricity consumption completely or can increase its consumption from its average usage level to its maximum load (assumed to be 4.5 kW).[28]

There is a limited need for regulation in the PJM market (roughly 660 MW currently).[29] Our analysis considers only the marginal effect of the Fast Response strategy and does not account for any potential reduction in the price paid for regulation services if water heaters bid into the market in large quantities. Regulation prices in PJM were especially high in 2014 compared to earlier years due to the January "Polar Vortex."[30] Thus, our estimates using the PJM 2014 market prices tend to be the higher end of the benefits.

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[27] See discussion later in this section of the report for a detailed description of the market scenarios.

[28] Because MISO and PJM do not have separate Reg-Up and Reg-Down products, suppliers must be able to provide equal amounts of regulation in both directions. Therefore, we model the amount of regulation a water heater can provide each hour as the minimum of the Reg-Up it can provide (average hourly load minus zero) and Reg-Down it can provide (maximum load of 4.5 kW minus average hourly load).

[29] See Monitoring Analytics (2015b).

[30] The Polar Vortex was an extreme weather event affecting the Eastern U.S. in late 2013 and early 2014. Record low temperatures caused an unexpected increase in demand for energy to heat homes and businesses, causing spikes in fuel and electricity prices.

Our estimate of frequency regulation value includes both regulation capacity payments and regulation "mileage" payments, as is allowed in PJM.[31] Capacity payments are designed to compensate a resource for the amount of capacity reserved to provide regulation. Mileage payments compensate a resource for how much regulation service the resource was called to provide from the reserved capacity.

In addition to the ERWH demand response strategies, two strategies were analyzed for HPWHs. One includes an uncontrolled HPWH that provides energy savings due to improved energy efficiency, and the second incorporates control of the HPWH's load. Both of these strategies were analyzed for a 50-gallon tank.[32] The two strategies are:

Strategy #4: Uncontrolled HPWH. Whereas ERWHs directly generate heat to increase the water temperature in the tank, HPWHs move heat from surrounding air to the water in the tank. This can have significant energy efficiency benefits, though it is important to note that there is variation in the efficiency of HPWHs. In particular, their dependence on heat in the surrounding air makes them better suited for warmer environments rather than cooler environments. In the Uncontrolled HPWH strategy, the water heater is not controlled but is more energy efficient than an ERWH, representing roughly a 50% reduction in energy needs.[33] We have assumed the Energy Star standard, which aligns with the findings of a recent report by the Northwest Energy Efficiency Alliance (NEEA).[34] All benefits of this strategy are derived from an overall reduction in the customer's water heating load profile.

Strategy #5: Controlled HPWH. In the controlled HPWH strategy, HPWH load is curtailed in a manner consistent with the Peak Shave strategy for ERWHs. Given general uncertainty around the ability of HPWHs to provide DR, we assume the most basic form of DR (peak shave) and base performance on findings of a recent NEEA report.[35] Uncertainty in the DR capability of HPWHs is driven by the relatively low and uniform load necessary to heat water with this technology. It is not clear that this load can be interrupted with the duration and frequency necessary to

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[31] In addition, PJM assigns a 'benefits factor' to fast-ramping RegD resources of between 0 and 3. Revenues to PJM RegD resources are multiplied by the benefits factor. We assume a benefits factor of 1, based on recent history. We also do not reduce revenues to account for performance scores, which could slightly affect revenues.

[32] These strategies could also be applicable to an 80-gallon tank, but we view it as unlikely that customers would have an economic incentive to increase storage capability under either of these HPWH strategies. Further analysis could explore this issue.

[33] Given the significant variability in the efficiency of HPWHs depending on surrounding air temperature, the sensitivity of the findings to this assumption should be tested through further analysis.

[34] See NEEA (2015).

[35] Ibid.

incorporate advanced load control strategies while maintaining adequate water temperatures. However, it is possible that emerging technology will enable this capability in the future.

A summary of all of the modeled water heating strategies in this analysis is provided in Figure 2.

Figure 2: The Modeled Electric Water Heating Strategies

	Uncontrolled	Peak Shave	Thermal Storage	Fast Response
ERWH, 50 gallon	Baseline	✓	✓	✓
ERWH, 80 gallon		✓	✓	✓
HPWH, 50 gallon	✓	✓		

With water heating load control programs, it is important to ensure that customers will not run out of hot water due to over-curtailment of load during or immediately preceding the time when customers need hot water. This could lead to low program participation and/or a decrease in customer satisfaction. Therefore, we developed reasonable assumptions about the operational capabilities of these programs that would not violate this constraint. Specifically, we relied on a study that simulated each of the water heating load control strategies for a diverse sample of customers. The study used detailed simulations of water heater operations across customers with a representative range of water heating needs to ensure that the strategies being modeled would limit the likelihood of hot water a runout to an acceptable level. The study, by Dr. Carl Hiller of Applied Energy Technologies, titled "Demand Controlled Electric Water Heater Diversified Electrical Demand Study" is provided in Appendix A.

BENEFITS AND COSTS

The cost-effectiveness of each water heating strategy was assessed from the system (or "societal") perspective.[36] The analysis accounts the total system benefits and costs of each strategy. Ultimately, how the societal costs and benefits would be shared by the utility, participants, and non-participants, such as generators or other customers, would depend on how participation incentives are structured and on the way in which program costs are recovered. The cost-effectiveness framework used in this study is a common approach adopted by many state regulatory commissions and utilities when evaluating the economics of demand-side opportunities.[37]

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[36] For further information on cost-effectiveness analysis of DR programs, see Hledik and Faruqui (2015).

[37] It is commonly referred to as the total resource cost (TRC) test. It was established in the California Public Utility Commission's Standard Practices Manual (SPM). See CPUC (2001).

Financial benefits in the analysis include:

- **Generation capacity**: Reductions in water heating load during peak times can avoid or defer the need for new generation capacity to serve growth in system peak demand.

- **Transmission & distribution (T&D) capital investments:** Peak load reductions can avoid or defer the need for new T&D investments that are driven specifically by system peak demand growth. It should be noted that the analysis does not include benefits related to location-specific deployment of DR on the distribution system. This is an emerging area of interest which, if effectively implemented, could potentially lead to larger benefits that are calculated in this study.

- **Energy:** Reducing load during high priced hours leads to a reduction in energy costs. This could be achieved either through an overall reduction in energy consumption from HPWHs, or by shifting load from higher cost hours to lower cost hours with ERWHs. In the latter case, the analysis estimates net avoided energy costs, accounting for costs associated with the increase in energy consumption during lower cost hours. The energy benefit accounts for avoided average line losses. Our analysis likely includes a conservative estimate of this value, as peak line losses are greater than off-peak line losses.[38] Our analysis does not include the effect of any potential change in energy market prices that may result from changes in load patterns (sometimes referred to as "wholesale price mitigation" or "price suppression"). It is simply a calculation of reduced resource costs.

- **Frequency Regulation:** As discussed earlier in this section of the report, short, frequent increases or decreases in water heating load can provide real-time balancing of supply and demand for electricity.

Additionally, this study includes an assessment of the potential changes in CO_2 emissions from conventional generators that could be attributable to reduced or shifted of water heating load. The impact of the change in CO_2 emissions is not included as a financial benefit, but the potential change in emission is quantified. This is discussed further in Section III.

All costs in the analysis are modeled as incremental to the baseline scenario of an uncontrolled 50-gallon ERWH. For all of the strategies, there are incremental costs associated with program administration, marketing, and recruitment. Incremental costs for a controlled 50-gallon ERWH include load control equipment and installation costs, mixing valve equipment and installation

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[38] Line losses increase with current flow, which tends to be higher during peak load hours. See PJM (2007) for more information.

costs,[39] and additional control equipment costs for the provision of ancillary services in the Fast Response scenario. Incremental costs for a controlled 80-gallon ERWH include these same control technology costs as well as an incremental cost associated with the larger tank (relative to the 50-gallon baseline). Similarly, for HPWHs, there is a significant incremental cost associated with the water heater and its installation. A summary of costs for each strategy is provided in Table 1. Additional assumptions in the cost-effectiveness analysis are provided in Appendix B.

Table 1: Summary of Incremental Costs Relative to Baseline (Annualized Cost per Water Heater)

	ERWH: Peak Shave		ERWH: Thermal Storage		ERWH: Fast Response		HPWH: Uncontrolled	HPWH: Controlled
	50 gal	**80 gal**	**50 gal**	**80 gal**	**50 gal**	**80 gal**	**50 gal**	**50 gal**
Incremental water heater cost	$0	$100	$0	$100	$0	$100	$727	$727
Equipment cost	$100	$100	$200	$200	$500	$500	$0	$100
Equipment installation cost	$150	$150	$200	$200	$200	$200	$0	$150
Program and marketing costs	$30	$30	$30	$30	$30	$30	$0	$30

Sources and Notes:
Incremental water heater costs derived from a review of commercial vendors. Other costs derived from a range of sources, including correspondence with industry experts and DR implementation firms as well as a review of EPRI (2014). All costs are annualized over the life of the water heater. Fast Response load control equipment cost was lowered by $200 in MISO 2028 scenario to account for the observed downward trend in technology cost and an expectation that this trend will persist into the future as the market matures. Peak Shave equipment and installation costs are lower than other scenarios to reflect no need for mixing valve with that strategy.

MARKET SCENARIOS

The benefits of any given water heating strategy can change significantly depending on the market conditions in which they are operating. To account for the effect of varying market conditions on the economics of the water heating strategies, the strategies were analyzed under three distinctly different market scenarios. To reflect "current" system conditions, we considered two markets, PJM East and MISO (Minnesota hub), using market data from 2014. The third scenario was designed to represent a distinctly different future state of the market. In developing this scenario, we relied on a pre-existing projection of the MISO market in 2028 that assumed increasingly stringent environmental regulations. The three market scenarios are described in more detail below.

PJM (2014). In 2014, prices in the PJM capacity market were moderate (around $50/kW-yr). Due to the Polar Vortex, energy prices were relatively high and frequency regulation prices were

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[39] A mixing valve regulates the temperature of the water coming out of the tank such that the water in the tank can be heated above the standard threshold of 120 degrees without increasing the risk of scalding. See Appendix A for further discussion.

very high. The mix of marginal fuel was roughly 46% natural gas, 49% coal, and 5% renewables.[40] We specifically used data from the PJM Eastern Hub to the extent possible.

MISO (2014): Recently, most parts of MISO have been long on capacity, so capacity market prices have been negligible. Due to the capacity surplus and a mix of low variable cost generation sources, energy and ancillary services prices were also low in 2014 relative to PJM. The mix of marginal fuel was roughly 23% natural gas, 75% coal, and 1% renewables.[41] It should be noted that, while MISO capacity prices were low, it is possible that certain pockets of the market could still have a capacity need and would therefore have higher capacity value than is represented in this scenario. We specifically used data from Minnesota Hub to the extent possible.

MISO (2028): This future scenario is based on the "Environmental" scenario in MISO's 2014 MISO Transmission Expansion Planning (MTEP) study.[42] MISO's "Environmental" scenario in its 2014 MTEP study was selected purely for illustrative purposes. All assumptions in the scenario were defined by MISO in its MTEP study and used directly, to the extent possible, in our analysis. It includes a \$50/ton CO_2 price, higher natural gas prices than realized in 2014, significant coal plant retirements relative to 2014, and growth in wind and natural gas generation capacity. The net effect of these market changes leads to higher energy prices. In this MISO 2028 scenario, we assume that the market reaches a point when the capacity surplus that currently exists in MISO has diminished, causing capacity prices to reach the net cost of new entry (net CONE).[43] Due to a larger share of renewables market penetration, we assume regulation prices reach those observed in PJM in 2014. The marginal fuel is estimated to be roughly 50% natural gas, 45% coal, and 5% renewables.[44]

To understand the market conditions that are being represented in the MISO 2028 scenario, it is important to distinguish between the near-term and longer-term effects that changes such as those represented in the MISO 2028 scenario may have on the market.

<u>In the near term</u>, low variable cost wind generation is added to the bottom of the supply stack. Inefficient fossil fuel-fired units are likely to be pushed off of the margin as a result. More of this

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[40] See Monitoring Analytics (2015a). The PJM 2014 marginal fuel mix included 10% from other sources. For simplicity, we have assumed "other" generation to be natural gas in these totals.

[41] See Potomac Economics (2015). Totals may not add due to rounding.

[42] See MISO (2014).

[43] CONE represents the first-year total net revenue (net of variable operating costs) a new generation resource would need in order to recover its capital investment and fixed costs, given reasonable expectations about future cost recovery over its economic life. It is the starting point for estimating the Net Cost of New Entry (Net CONE). Net CONE is defined as the operating margins that a new resource would need to earn in the capacity market, after netting margins earned in markets for energy and ancillary services. For further discussion, see Newell et al. (2014).

[44] See Monitoring Analytics (2015a).

displacement is likely to occur in the night/evening hours than during the day due greater output from wind facilities during those night/evening hours. This may reduce the marginal CO_2 emissions rate more during off-peak hours than during peak hours in MISO today. This should reduce wholesale energy market prices and also continue to keep capacity prices low due to excess generation capacity (assuming no significant near-term retirements). While the increase in adoption of renewables will mean a greater need for flexible resources, the capacity surplus could mean that a significant amount of flexible generation capacity is idle and available to provide these ancillary services.

Further, in the near term, if large amounts of wind are added to the system, there could be significant wind curtailment during hours of low net load (i.e., night and shoulder seasons) and in transmission constrained areas (e.g., as has been observed in Texas and Hawaii).[45] The potential for the water heaters to use the wind energy that would otherwise be curtailed during off-peak hours could improve the environmental benefits of water heating load. Economic benefits would likely decrease due to depressed energy and capacity market prices.

<u>In the future</u>, generation units should eventually be retired due to the reduced energy and capacity prices described above. Reserve margins will shrink and energy and capacity prices could return roughly to the levels required to support new entry of generation, which would be net CONE under these conditions. Wind curtailment is likely to be reduced – though probably not eliminated - through the addition of new economic transmission capability, improvements in grid operations, and other means. The introduction of a carbon price would lead to further increased energy prices and potentially the retirement of some coal units, putting gas on the margin in more hours. Ancillary services prices could plausibly increase as reserve margins tighten.

A summary of the market prices in the three scenarios is provided in Table 2, highlighting the distinct differences between the market scenarios.

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[45] See Bird et al. (2014).

Table 2: Summary of Market Scenarios

	Generation Capacity Price	Marginal T&D Cost	Energy Price	Frequency Regulation Price
PJM (2014)	Medium ($50/kW-yr)	Medium ($30/kW-yr)	Medium ($59/MWh)	High ($44/kW-yr)
MISO (2014)	Low ($1/kW-yr)	Medium ($30/kW-yr)	Low ($33/MWh)	Low ($11/kW-yr)
MISO (2028)	High ($87/kW-yr)	Medium ($30/kW-yr)	High ($69/MWh)	High ($44/kW-yr)

Notes:
The MISO 2028 scenario is not necessarily a projection of the most likely future state of the MISO market. It is loosely based on the “environmental” scenario in MISO’s 2014 MTEP study and was selected to represent one distinctly different plausible future state of the market, for the purposes of illustrating how the economics of water heating strategies would change under these alternative market conditions.

Sources:
Energy prices from Velocity Suite, ABB Inc. PJM East (2014) energy price from 2014 PJM Eastern Hub hourly prices, MISO (2014) energy price from MISO Minnesota Hub hourly prices. MISO (2028) energy price from the 2028 ‘Environmental’ scenario in MISO’s 2014 MTEP study, see MISO 2014. T&D capacity prices based on a review of common avoided cost assumptions in utility DR filings. Frequency regulation prices from Velocity Suite, ABB Inc. Regulation prices for PJM East (2014) and MISO (2028) is based on average 2014 PJM regulation price. Frequency regulation price for MISO (2014) based on average MISO 2014 regulation price. PJM East capacity price based on clearing price of the 2014/15 Base Residual Auction for the MAAC region, see PJM 2011. MISO (2014) capacity price based on 2015/16 capacity auction clearing price of $3.48/MW-day for the majority of MISO zones. MISO 2028 capacity prices calculated based on the estimated net cost of new entry (net CONE) of a new combined cycle unit, assuming gross CONE of $172.6/kW-yr (2018 dollars), ancillary service revenues of $3,198/kW-yr (2018 dollars), and energy revenues based on MISO’s 2028 “Environmental” scenario, see Newell et al. (2014).

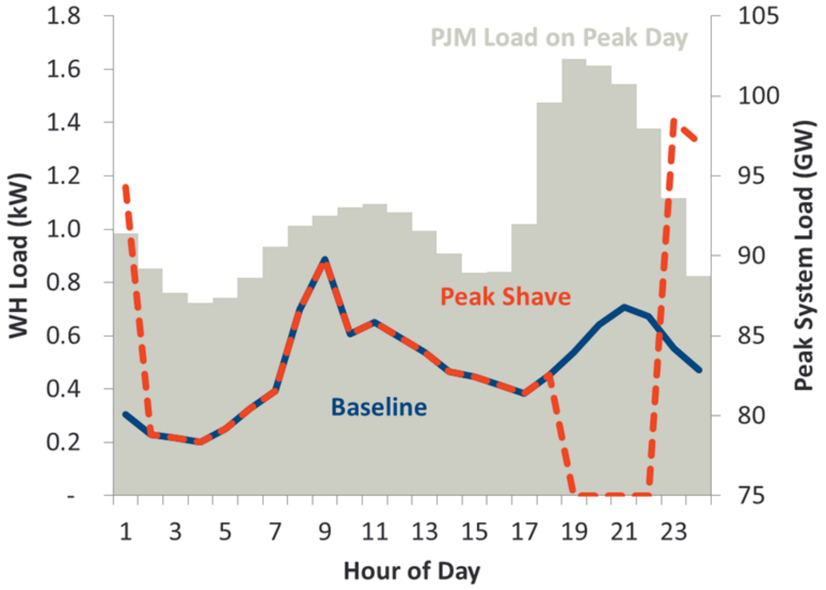
III. Analysis of the Five Strategies

This section summarizes the costs and benefits of each of the water heating strategies at the individual customer level, the impact of the water heating strategies on CO_2 emissions, and the potential impacts of a portfolio of water heating strategies at the aggregate system level.

THE PEAK SHAVE STRATEGY

The Peak Shave strategy reduces water heating load during the highest system peak demand hours of the year. Based on the water heating simulations developed for this study, a 50-gallon tank can be interrupted for up to four hours with little risk of running out of hot water across a range of customers with diverse hot water needs.[46] We have assumed that the curtailment of the water heating load would occur during afternoon hours of summer months in MISO and PJM, when the demand on the power system is typically peaking. Relative to the baseline load profile illustrated in Section II, this would lead to a system coincident peak demand reduction of approximately 0.5 kW per water heater. That is the average load of the baseline water heater during the peak hours when the load is curtailed. This is illustrated in Figure 3.

Figure 3: The Peak Shave Strategy (50-gallon tank), Illustrative Peak Load Day



The system peak load reductions provided by the Peak Shave strategy make it particularly economic in markets where there is a need for new generating capacity. Net benefits per water heater in the PJM 2014 and MISO 2028 scenarios are $13 and $29 per customer per year,

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[46] This requires the installation of a mixing valve and heating the water in the tank to 160 degrees. See Appendix A for details.

respectively. At very low capacity prices such as those in the MISO 2014 scenario, however, the avoided costs do not overcome the incremental cost of the equipment needed to control the water heater, with a net benefit of -$15 per customer per year. A detailed breakdown of the costs and benefits of each strategy can be found in Appendix C.

The Peak Shave strategy does not require investing in a larger tank size; the incremental cost associated with investing in the larger tank makes that approach less economic than using a 50-gallon tank. A decision to invest in larger tanks in this case would be driven by non-economic factors, such as safety concerns about overheating the water or concerns about running out of hot water.

THE THERMAL STORAGE STRATEGY

The Thermal Storage Strategy captures energy benefits in addition to capacity. Water is heated to a maximum acceptable temperature at night and then heating is curtailed to reduce load during hours with high system energy and capacity prices. The storage capability of the 50-gallon tank allows for curtailments of up to 4 hours per day; longer curtailments would either lead to an unacceptable risk of hot water shortages or require that the water in the tank be pre-heated to unacceptable levels. Alternatively, the larger storage capability of the 80-gallon tank allows it to be curtailed up to 16 hours per day without violating the constraints described above.[47] This is illustrated in Figure 4.

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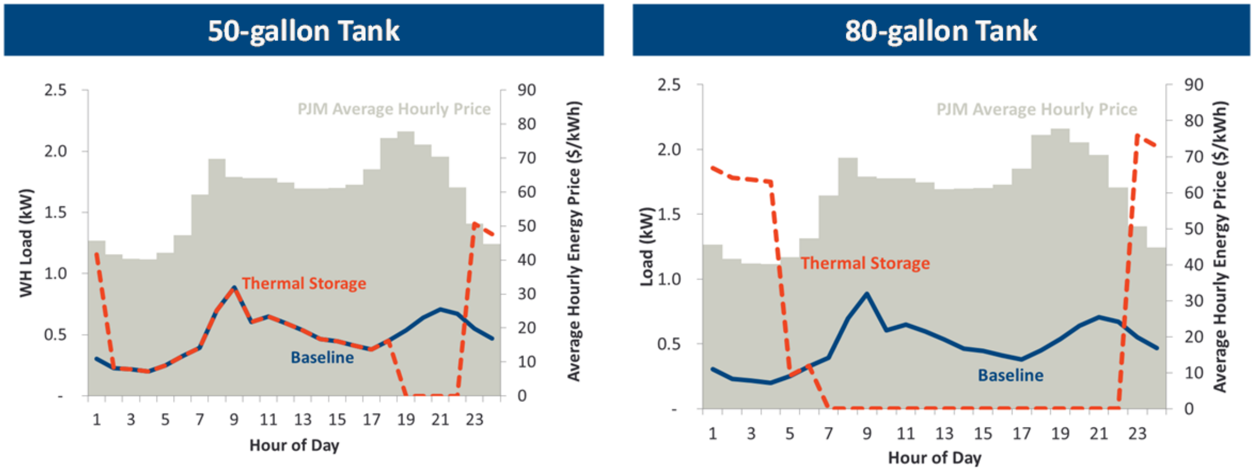
[47] Note that, with the larger tank, in some select cases customers would need to be equipped with a ~100-gallon tank in order to achieve the full 16 hours of curtailment with minimal risk of hot water shortages. Both tank sizes also require a mixing value, which allows the max temperature of the water in the tank to be increased, therefore reducing the possibility of hot water shortages when curtailing load on a daily basis

Figure 4: The Thermal Storage Strategy

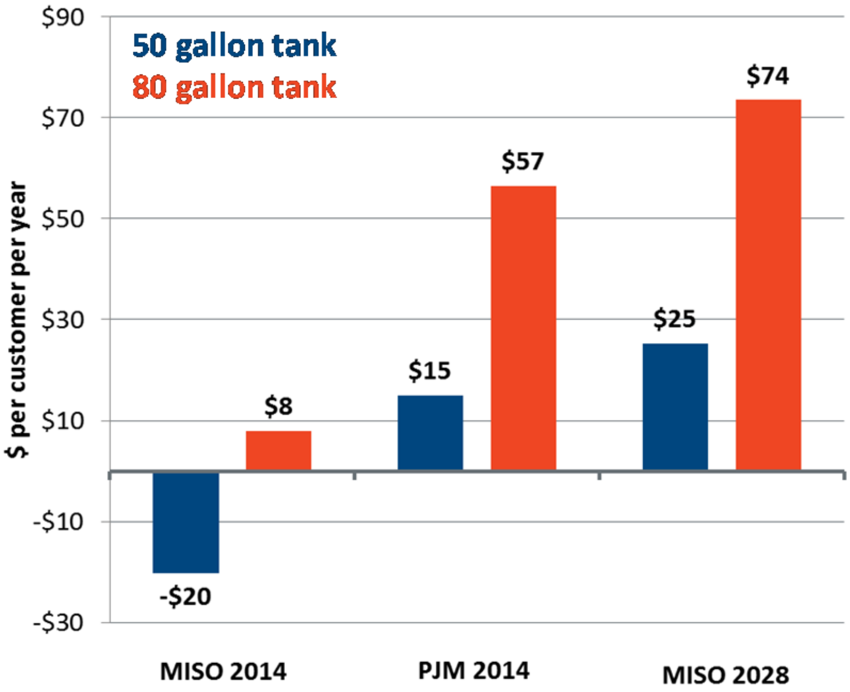


Source:
Hourly day ahead wholesale price data for 2014 PJM East Hub from Velocity Suite, ABB Inc.

For a 50-gallon tank, the Thermal Storage strategy may increase net benefits relative to the Peak Shave strategy by as much as $2 per customer per year or decrease net benefits by as much as $5 per customer per year. While the Thermal Storage strategy captures energy value in addition to capacity value, equipment and installation costs are higher than the Peak Shave scenario due to the need for a mixing value, offsetting the increase in benefits in some cases. Further, due to constraints on the small tank's hot water storage capability, energy value is somewhat limited, since the small water heater can only be curtailed four consecutive hours per day.

A larger 80-gallon tank dramatically improves the economics of the Thermal Storage strategy. The larger tank can be curtailed for many more consecutive hours without risking running out of hot water. With a significant number of hours with high energy prices and a large price differential between peak and off-peak prices, the benefits of increasing the tank size justify the incremental cost of the larger tank, and the ability of the larger tank to store more hot water can significantly increases the avoided energy cost. With a larger tank, the economics of water heating load control are cost-effective even at the relatively low capacity and energy prices of the MISO 2014 scenario. A comparison of the net benefits of the Thermal Storage strategy for 50- and 80-gallon tanks is shown in Figure 5.

Figure 5: Net Benefit of Thermal Storage for 50-gallon versus 80-gallon tank

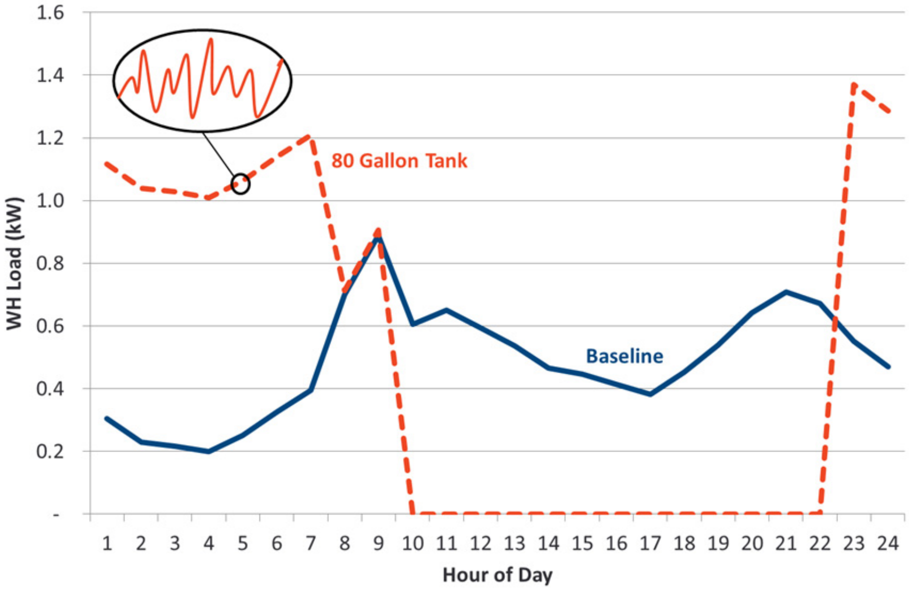


Note:
MISO 2028 includes a CO_2 charge, the direct impact of which is not reflected in the results shown here. Net benefits would decrease by about $10 in that scenario for the 80-gal tank and $2 for the 50-gal tank due to a slight increase in associated emissions. See Appendix B for further discussion.

THE FAST RESPONSE STRATEGY

The Fast Response strategy provides real-time response to fluctuations in supply. The load profile is similar to that of the Thermal Storage strategy, but with short-duration, high-frequency fluctuations in load around the average profile. As defined by the PJM RegD product, these fluctuations are "energy neutral" on an hourly basis, so there is no significant additional concern about over- or under-heating the water in the tank. These fast response services would be provided on a daily basis. An illustration of the Fast Response strategy is provided in Figure 6.

Figure 6: Illustration of the Fast Response Strategy



The Fast Response strategy requires more expensive control equipment than the previously discussed strategies, as there are additional requirements associated with being able to provide frequency regulation (such as having control equipment that is capable of receiving and responding to the system operator's high-frequency control signal). Based on a review of material on the economics of grid interactive water heaters, we have assumed an equipment cost premium of $400 per water heater (an annualized cost of $47) to account for these requirements.[48] This advanced control technology is only beginning to become commercially available and costs could decrease significantly over time. Given an observed downward trend in these technology costs and an expectation that this trend will persist as the market matures, we use an illustrative assumption that the cost premium will drop to $200 per water heater (annualized cost of $23) in the MISO 2028 scenario.

While the costs of the Fast Response strategy increase, so do the benefits. In the PJM 2014 scenario, for example, gross benefits increase from $118 per customer per year with the Thermal Storage strategy to $269 with the Fast Response strategy. A detailed breakdown of the costs and benefits under these two strategies is provided in Figure 7. As market adoption of the technology increases and experience grows, it is possible that the more sophisticated control technology will provide additional benefits, such as a refined algorithm that maximizes load reductions during high priced periods and/or minimizes the potential for undersupply of hot water.

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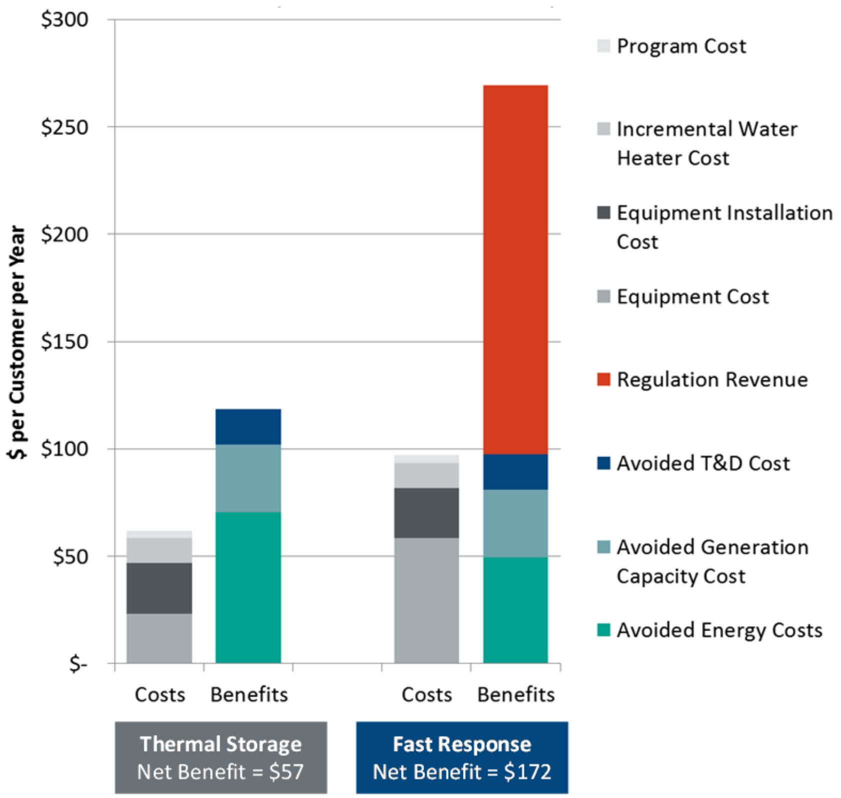
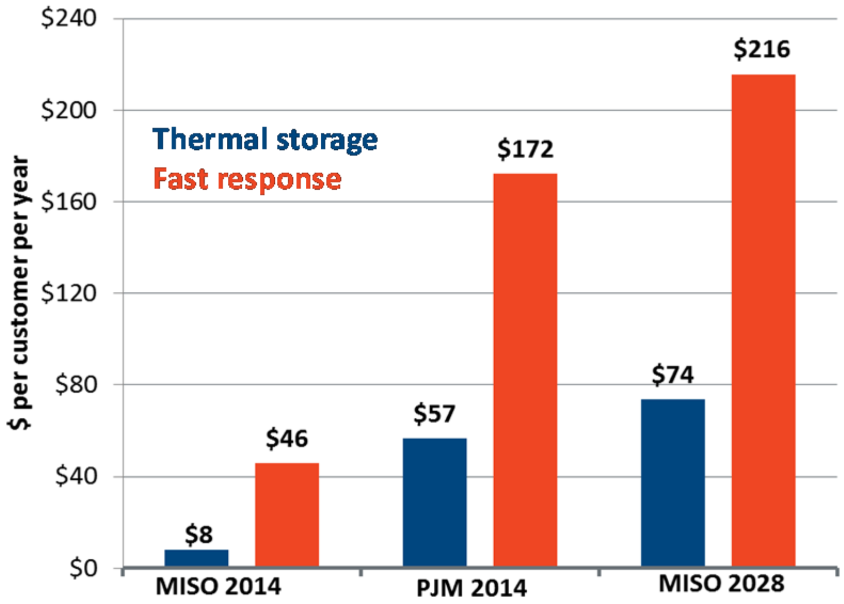
[48] Correspondence with manufacturers and a review of publicly available documentation suggests that the incremental cost of "grid interactivity" in a water heater is roughly in the range of $300 to $500. See PJM et al (2012) for one estimate. We have assumed $400, the midpoint of this range, as the incremental cost.

Figure 7: Costs and Benefits for 80-gallon Tank, PJM 2014 Scenario



The Fast Response strategy can produce the largest net benefits when ancillary services prices are high. Across all three of the market scenarios analyzed in this study, frequency regulation value is greater than the incremental equipment cost premium necessary for fast load response. This net increase in benefits means that the economics of water heating load control improve relative to the Thermal Storage case, increasing by between $38 and $142 per customer per year, depending on the market scenario. A comparison of the Fast Response and Thermal Storage strategies is provided for an 80-gallon water heater in Figure 8. We note that regulation prices in PJM were especially high in 2014 compared to earlier years due to the winter "Polar Vortex."

Figure 8: Net Benefits of Fast Response versus Thermal Storage Strategy for 80-gallon Tank



Note:
MISO 2028 includes a CO_2 charge, the direct impact of which is not reflected in the results shown here. Net benefits would decrease by about $7 in that scenario for Fast Response and $10 for Thermal Storage due to a slight increase in associated emissions. See Appendix B for further discussion.

The incremental boost in net benefits attributable to the Fast Response strategy is greatest for 50-gallon tanks. Under the Fast Response strategy, 50-gallon tanks produce net benefits that are similar in magnitude to those of the 80-gallon tanks.[49] However, this finding regarding the smaller tank size is driven partly by the fact that the Fast Response strategy is not modeled to perfectly optimize the three value streams. In practice, the larger tank should provide greater revenue opportunities, particularly in markets where regulation up and regulation down could be sold as separate products.

THE UNCONTROLLED HPWH STRATEGY

The Uncontrolled HPWH strategy is purely an energy efficiency strategy. This scenario simply assumes that customers invest in an efficient HPWH and do not provide demand response or frequency regulation services. Modeling a "representative" HPWH is challenging because its performance varies considerably based on ambient air temperature. HPWHs perform significantly better in warmer environments, where heat can be drawn from the surrounding air

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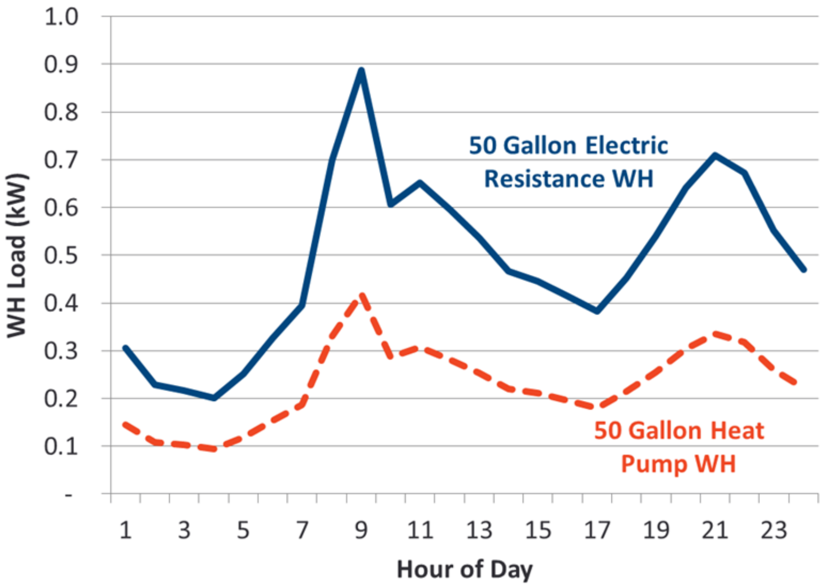
[49] This is largely because, consistent with the design of PJM's RegD market, control of the water heater is energy neutral on an hour-by-hour basis. That feature lessens the importance of tank size by ensuring that any decrease in water temperature due to load curtailment will be offset by an increase in water temperature due to an equal load increase over the course of the hour.

to heat the water in the tank. As such, their efficiency can vary by climate zone, their location within the home (garage, basement, or interior), and the inlet water temperature. We assume the new HPWHs have an energy factor of 2, as required by the Energy Star Standard.[50]

Despite differences between HPWH technology and that of an ERWH, the average HPWH load profile roughly represents a proportional reduction in the load shape of an ERWH due to load shape diversity across customers. The load profile of the 50-gallon HPWH relative to the baseline ERWH is illustrated in Figure 9. We only model a 50-gallon tank for the Uncontrolled HPWH scenario, assuming that it has been fully meeting the customers' hot water needs in the baseline case. Given that storage capability is not an input to this strategy, we assume there would be no need for a larger tank.

Figure 9: Illustration of the Uncontrolled HPWH Strategy



Note:
Assumes a 0.94 energy factor for the baseline ERWH and a 2 energy factor for the HPWH

The HWPH has the potential to provide significant energy efficiency benefits; in our analysis we assumed a reduction in water heating energy needs of approximately 50%. The HPWH also provides some capacity value due to lower average consumption during the hours of the system peak. These efficiency benefits are partly offset by the higher equipment and installation costs of the HPWH, which represents an incremental cost of approximately $730 per water heater relative to the baseline (or annualized cost of $85 per water heater). The uncontrolled HPWH is, therefore, most cost-effective in markets with high average energy prices. Across the three

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[50] The "energy factor" is based on the amount of hot water produced per unit of fuel consumed. A higher energy factor indicates a more efficient the water heater.

scenarios analyzed in this study, annual net benefits per customer are $2 for the MISO 2014 scenario, $76 for the PJM 2014 scenario, and $65 for the MISO 2028 scenario.[51]

THE CONTROLLED HPWH STRATEGY

The Controlled HPWH strategy is a Peak Shave strategy combined with the efficiency benefits of a HPWH. This strategy assumes that customers invest in an efficient HPWH and that water heating load is curtailed to reduce the system peak on the limited number of days when the system peak is likely to occur. It should be noted that there is debate as to whether or not HPWHs can provide demand response benefits. This is because the water heating process of a HPWH generally requires a low level of fairly constant heat, as opposed to ERWH which have an electric heating element that is frequently turned on and off as needed to maintain the desired water temperature. Some argue that this technological difference is a constraint which would lead to an unacceptable risk of hot water shortages if HPWH load were curtailed for a significant amount of time. Others argue that hybrid HPWHs, which have an electric heating element in addition to the standard heat pump, would overcome this barrier to providing reliable load reductions. To represent the demand response capability of HPWHs, we have based the performance of the controlled HPWH roughly on the findings of a 2015 study by the Northwest Energy Efficiency Alliance (NEEA).[52] An illustration of the Controlled HPWH strategy is presented in Figure 10.

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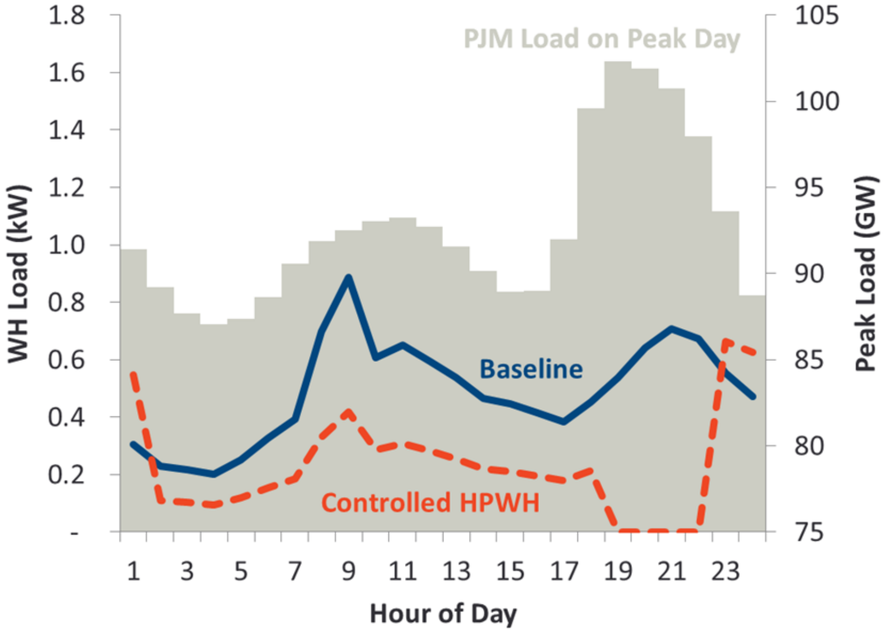
[51] MISO 2028 includes a CO_2 charge, the direct impact of which is not reflected in the results shown here. Net benefits would increase by about $40 in that scenario due to a decrease in associated emissions.

[52] See NEEA (2015).

Figure 10: Illustration of the Controlled HPWH Strategy, Illustrative Peak Load Day



Note:
Assumes a 0.94 energy factor for the baseline ERWH and a 2 energy factor for the HPWH.

Across the market scenarios analyzed in this study, the inclusion of load control capability only modestly affects the net benefits of a HPWH. This is because a significant portion of the potential capacity benefit is already captured through the reduced peak period load that results from the unit's improved efficiency. In other words, the uncontrolled HPWH already captures a sizeable capacity benefit, leaving only a modest incremental amount to be captured through load control. As a result, the incremental capacity benefit of the peak load reductions is roughly offset by the additional cost of the control technology.[53] If technological advances allowed HPWHs to provide load reductions are that are more frequent or longer in duration, the economics of this strategy could improve. The net benefits of the Controlled HPWH strategy relative to the Uncontrolled HPWH strategy are summarized in Figure 11.

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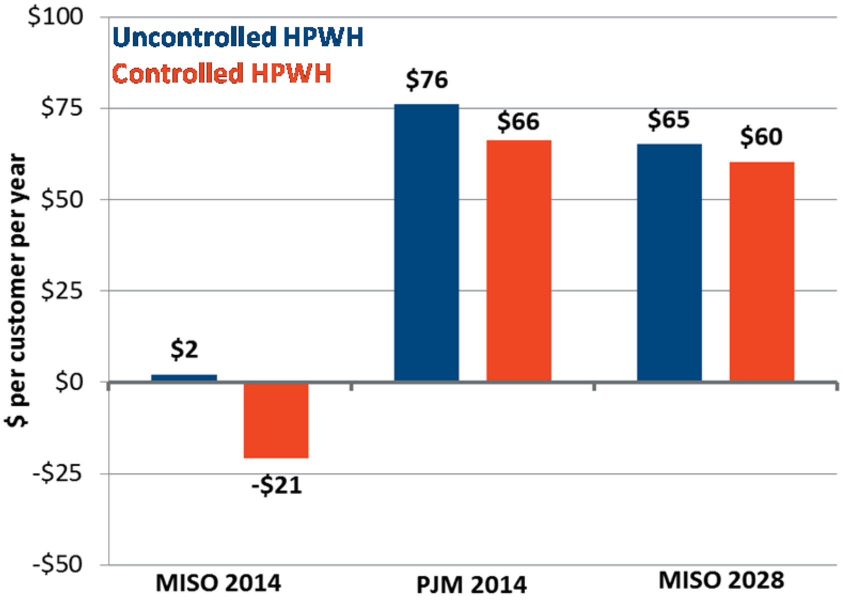
[53] We assume the same costs of the control technology as with the ERWH Peak Shave strategy.

Figure 11: Net Benefits of Controlled versus Uncontrolled HPWH



Note:
MISO 2028 includes a CO_2 charge, the direct impact of which is not reflected in the results shown here. Net benefits would increase by about $40 in that scenario due to a decrease in associated emissions. See Appendix B for further discussion.

SUMMARY OF SYSTEM FINANCIAL BENEFITS

Across the five water heating strategies analyzed in this study, the Fast Response strategy for the ERWH has the greatest potential net system benefits and could work well with a range of tank sizes. The benefits of the Thermal Storage strategy with a large tank are perhaps the most robust across a range of market conditions, because at very low ancillary services prices the benefits of the Fast Response strategy may not outweigh the incremental costs of the additional technology. The Peak Shaving strategy is likely best suited for situations where customers require the most minimally intrusive program or otherwise have a very high sensitivity to the possibility of a hot water shortage. The efficiency benefits of HPWHs are significant and robust across market conditions, but their applicability is limited due to technical requirements (e.g., physical footprint) and performance constraints determined by local conditions (i.e., water and air temperatures). The net benefits of the five strategies across the three market scenarios are summarized in Table 3.

Table 3: Net Benefits Summary ($ per Customer per Year)

Water Heater	Strategy	PJM East (2014)	MISO (2014)	MISO (2028)
ERWH 50-gal	Peak Shaving	13	-15	29
	Thermal Storage	15	-20	25
	Fast Response	162	39	195
ERWH 80-gal	Peak Shaving	1	-28	19
	Thermal Storage	57	8	74
	Fast Response	172	46	216
HPWH 50-gal	Uncontrolled	76	2	65
	Peak Shaving	66	-21	60

Notes:
Darker shading indicates higher net benefit. MISO 2028 includes a CO_2 charge, the direct impact of which is not reflected in the results shown here. See Appendix B for further discussion.

ENVIRONMENTAL IMPACTS

In addition to the potential system benefits of the water heating strategies summarized above, it is also useful to consider their environmental impacts, particularly the impact on power system CO_2 emissions.

There are two primary ways in which the water heating strategies would impact CO_2 emissions. The first is attributable to a change in total energy consumption by the water heaters themselves. If the new water heater is more efficient than the baseline ERWH, as is the case with HPWHs, an overall reduction in energy consumption should lead to reduced CO_2 emissions. Similarly, if the new water heater is less efficient, as is the case with a larger ERWH, there could be an increase in CO_2 emissions.

The second way in which water heaters could impact CO_2 emissions is due to a change in the energy consumption pattern. When load is shifted from peak hours to off-peak hours, there will be a change in CO_2 emissions that depends on the marginal fuel in those hours. For instance, if natural gas is on the margin during peak hours and coal is on the margin during off-peak hours, there could be an increase in emissions due to the higher CO_2 emissions rate of the coal units. Alternatively, if inefficient gas units are on the margin during peak hours and a mix of efficient gas units and renewables are on the margin during off-peak hours, for example, there could be a reduction in CO_2 emissions.

The CO_2 emissions reduction of the water heating strategies will depend heavily on the marginal fuel mix. The three market scenarios analyzed thus far in this study all have a mix of coal and gas on the margin. While the proportions of those fuels vary somewhat, the marginal emissions profile is relatively flat over the course of the day across all three scenarios (see Appendix B for details). Emissions impacts from the water heating strategies remain consistent across these scenarios as a result. Thus, while the market scenarios are helpful for illustrating the range of system financial benefits that could be realized from new water heating strategies, they do not illustrate the range of potential CO_2 emissions impacts.

To better illustrate the range of potential CO_2 emissions impacts that could result from the water heating strategies, we consider an additional illustrative yet plausible case in which the marginal fuel is a mix of natural gas and renewables.[54] In such a scenario, there would be higher-emissions units on the margin during peak hours and lower- or zero-emissions units on the margin during off-peak hours. Specifically, we have assumed an illustrative case in which the marginal fuel is 70% natural gas-fired combined cycle, 20% natural gas-fired combustion turbine, and 10% renewables (solar, wind, and hydro).[55] We assume a realistic range of heat rates within the gas-fired unit categories, with less efficient units assumed to be on the margin during peak hours when load is high and vice versa. While this stylistic case is a different approach to quantifying the impacts of water heaters than the market price-based approach we have used to evaluate their economics, it provides a reasonable proxy for the magnitude of CO_2 impacts that could be observed in this market setting.

It is also important to note that the load shifting strategies analyzed in this study have been designed to maximize economic benefits, not environmental benefits. In other words, the assumptions around when the water heaters would be both curtailed and consuming electricity are driven by an interest in maximizing capacity, energy, and ancillary services value, without particular regard for the effect on emissions. A different curtailment strategy that accounts for CO_2 impacts could lead to greater emissions reductions. To account for this possibility, we constructed a case with coal and gas as the marginal fuels, but assumed that the water heater would largely be curtailed during hours when higher-emissions units (i.e., coal and older, less efficient gas-fired units) were on the margin and that this load would largely be shifted to hours when lower-emissions units (i.e., higher efficiency gas fired units) are on the margin. This stylistic case is labeled "environmental water heater curtailment" because the curtailment of the water heater is assumed to align with hours that would maximize the CO_2 benefits.

Across all scenarios analyzed, HPWHs provide consistent CO_2 emissions reductions per customer. The efficiency improvement of HPWHs results in a proportional reduction in emissions due to the around-the-clock nature of the energy savings. With ERWHs, the story is more nuanced. The emissions impact of ERWHs is driven by load shifting and depends on the emissions profile of the market. With a marginal fuel mix of natural gas and coal and economic curtailment of the water heater, the ERWH strategies can increase emissions by up to around 9%

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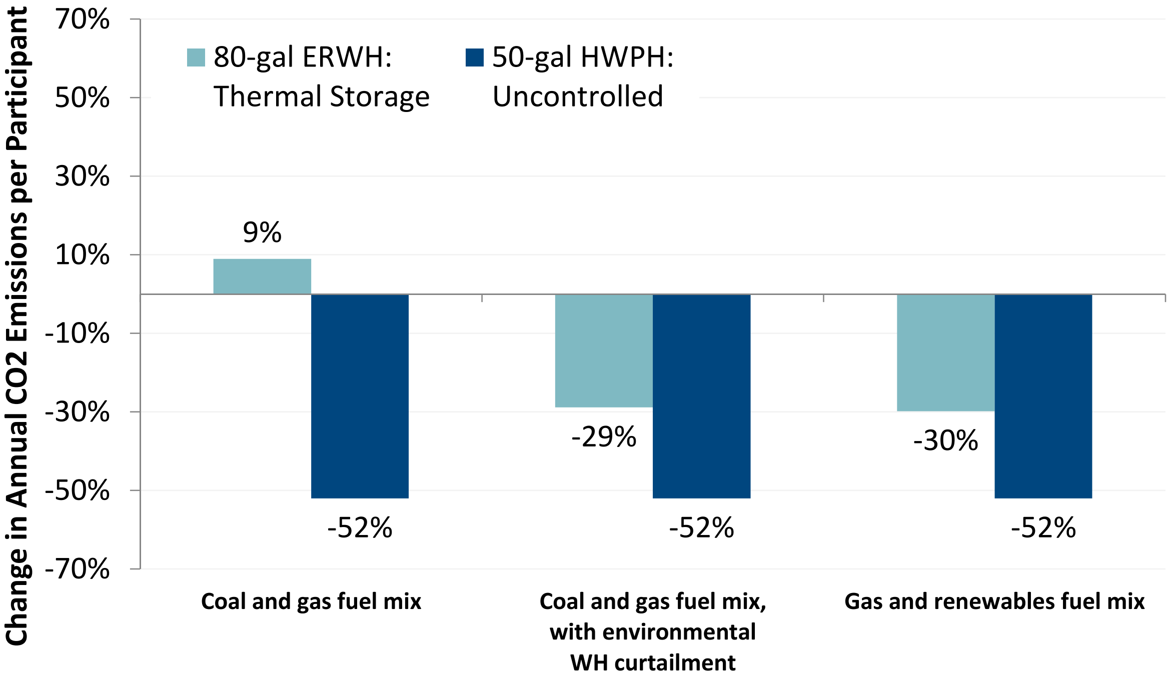
[54] For instance, in California, where there is no coal generation and nuclear units are inframarginal, natural gas and hydro compose the vast majority of marginal generating units, with some economic and manual curtailments of wind and solar as well.

[55] This would be a case where wind or solar are being curtailed due to over-generation and/or transmission constraints. Water heaters could be enrolled in DR programs in those particular locations on the grid where load increases would be valuable in reducing wind/solar curtailments.

due to shifting load from lower-emission hours to higher-emission hours, based on the specific assumptions in this study. However, in a scenario with coal and natural gas on the margin but with environmentally-oriented curtailment of the water heater, CO_2 emissions from water heating load could be reduced by roughly 29%. Similarly, in a scenario with gas and renewables as the marginal fuels and environmental curtailment of the ERWH, CO_2 emissions are reduced by roughly 30% per participant. This is illustrated in Figure 12.

Figure 12: Change in Water Heater CO_2 Emissions (Relative to Baseline Uncontrolled 50-gallon ERWH)



Notes:
Figure shows only two of many possible different marginal fuel mix scenarios; results can vary significantly based on the assumed fuel mix. Coal/gas scenario based on 2014 PJM market conditions. Gas/renewables scenario based on illustrative assumptions. Environmental water heater curtailment based on reasonable but illustrative assumptions about water heater operations. Overall impact of Peak Shave strategy on CO_2 emissions is negligible due to infrequent curtailments. Emissions of Fast Response strategy can differ slightly from those of Thermal Storage strategy due to different off-peak load pattern. Emissions of 50-gal tanks are lower than those of 80-gal tanks due to different efficiency levels. Efficiency benefit of HPWHs depends heavily on ambient air temperature. Total annual marginal CO2 emissions of baseline uncontrolled 50-gallon ERWH are 1.9 tons in the coal/gas scenario and 0.5 tons in the gas/renewables scenario.

While the example in Figure 12 illustrates the impact of the Thermal Storage strategy on emissions, it is also relevant to consider whether the provision of Fast Response services would provide additional environmental benefits. As market penetration of renewables increases, it is expected that there will be a growing need for flexible resources that can help to integrate this intermittent source of generation. While this will present a financial opportunity for ERWHs to provide ancillary services, it is not clear that there is a direct incremental environmental benefit. ERWHs load will quickly ramp up and down when providing ancillary services. Reductions in water heating load will necessarily be offset by an increase in water heating load at a different time within a relatively short interval in order to maintain an acceptable water temperature. In other words, as represented in our analysis and consistent with PJM's RegD product, providing ancillary services from a water heater is an energy neutral activity. As a result, the Fast Response strategy should not directly have a dramatic impact on total emissions in a static environment. However, there could be an emissions benefit if renewables are not being built simply due to a lack of flexibility in the system. In this case, controlled ERWHs could ease this constraint by providing a cost-effective and flexible resource, leading increase in adoption of zero-emissions renewables.

SYSTEM IMPACTS

The results presented in this report thus far have focused on marginal impacts at the individual customer level. They can be extrapolated to the system level with realistic assumptions about participation. To illustrate this, consider a small hypothetical utility in MISO with roughly 100,000 customers. Roughly consistent with national averages, we assume that 40% of the customers have an ERWH, 50% of those customers have a 40- to 50-gallon water tank, and 50% of those customers will be replacing their tank at some point in the next 10 years. This means that 10,000 of the utility's 100,000 customers are eligible to participate in a new water heating program.[56]

The hypothetical utility is considering promoting the following strategies:

- 50-gallon HPWH
- 50-gallon ERWH with a Peak Shave DR program
- 80-gallon ERWH with Thermal Storage DR program
- 80-gallon ERWH with Fast Response DR program

To pursue these options, the utility has a choice. It could offer just a single one of these options to customers (presumably the one that best meets its system needs), or it could offer customers a menu of options and allow the customer to enroll in the option of their choice.

Total participation will vary depending on which of these approaches is pursued by the utility. Offering a single program will maximize the participation in that single program. Offering a portfolio of programs will maximize the total participation in some form of water heating program. Based loosely on historical residential DR program enrollment data, participation rates could resemble those shown in Table 4.[57]

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[56] 100,000 customers x 40% x 50% x 50% = 10,000 eligible participants.

[57] Due to technical constraints, HPWH adoption is limited (less than 1% of the U.S. residential water heating market is HPWH). Total participation in the portfolio is assumed to be less than the sum of participation rates if the programs were offered in isolation, because customers can enroll in only one program when offered as a portfolio. Total participation in the portfolio is assumed to be greater than

Continued on next page

Table 4: Illustrative Water Heating Program Participation Rates (% of Eligible)

Water Heater	Strategy	When offered in isolation	When offered as portfolio
HWPH 50-gal	Uncontrolled	5%	4%
ERWH 50-gal	Peak Shaving	20%	10%
ERWH 80-gal	Thermal Storage	20%	15%
ERWH 80-gal	Fast Response	20%	15%
		Portfolio Total:	44%

With these participation assumptions, system-level benefits are likely to be greatest when programs are offered as a portfolio. A utility's residential customer base tends to be a fairly diverse and heterogeneous group. Customer preferences for different water heating program options will vary. For instance certain, customers may be attracted to the energy savings associated with a HPWH program, and therefore be willing to pay the up-front premium necessary to achieve those savings over time. Other customers simply may not have the option to install a HPWH due to the physical constraints of their home. Others may be interested in the low-risk Peak Shaving program, while others may be attracted to the financial upside of the Thermal Storage and Fast Response programs. A portfolio is effectively a diversified product offering that will maximize participation.

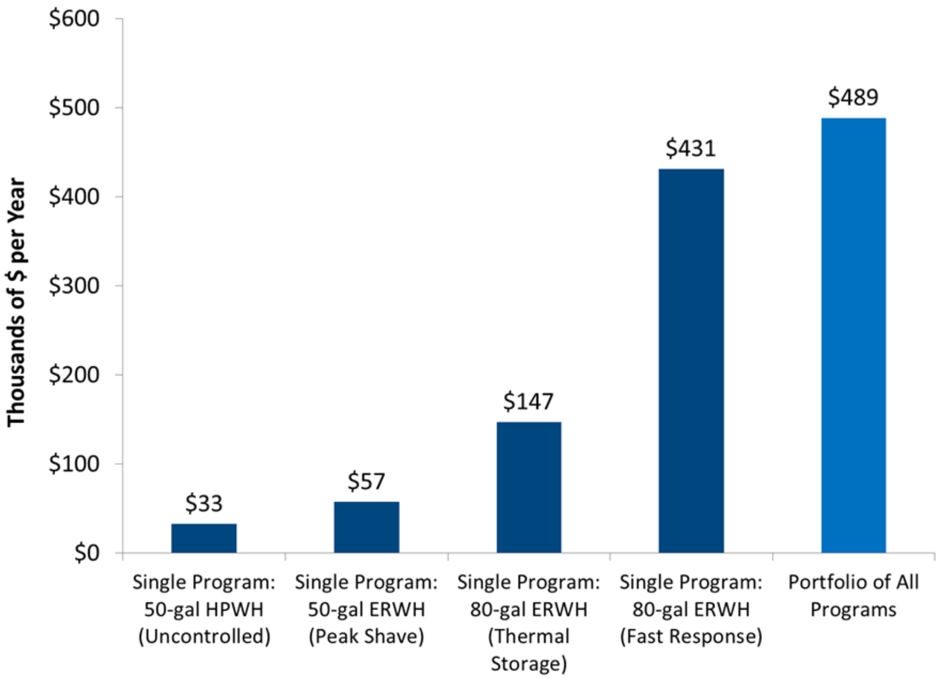
The benefits of the water heating strategies, both when offered in isolation and as part of a portfolio, are illustrated in Figure 13.[58]

Continued from previous page

participation in any single program offered in isolation, because a menu of distinctly different program options will appeal to a broader base of potential participants. See Appendix B for additional details.

[58] Note that the system-level net benefits estimated here do not consider the potential for stranded costs.

Figure 13: Annual System-Level Net Benefits for Utility with 100,000 Residential Customers (Thousands of Dollars per Year)



Notes:
Based on hypothetical utility with 100,000 residential customers in MISO (10,000 of which are eligible) using economic conditions of the "MISO 2028" market scenario. Does not reflect financial value of CO_2 emissions reduction. See Appendix B for further discussion.

When considering these estimates of system level impacts, it is important to note that they are simply a linear scaling of the per-customer impacts. The analysis does not take into account the "depth" of each market (capacity, energy, and frequency regulation) and assumes that there will be no significant marginal impact on the prices in any of these markets. In practice, particularly with respect to ancillary services markets, a substantial increase in participation by controlled water heaters could have an impact. For example, in PJM the need for frequency regulation in 2014 was on average 663 MW, relative to a system peak of more than 140,000 MW.[59] The extent to which growing adoption of these water heating strategies will affect the total value of the programs is an important issue for further research.[60]

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[59] See Monitoring Analytics (2015b).

[60] For an example of a study that has taken the depth of the market into account, see Chang et al. (2014).

IV. Conclusions and Recommendations

Electric water heaters have the potential to provide significant value to a power grid with a growing need for flexible resources and improved efficiency. The water heating strategies available – including both conventional approaches that have been used for decades and emerging options driven by recent technological advancement – each have their own advantages and beneficial applications. Specifically, this study has found that:

- The Peak Shave strategy is well suited for market conditions in which there is a peak demand-driven need for generation and/or transmission capacity, a relatively flat energy price profile, and/or a limited ability to promote adoption of larger ERWH tank sizes.

- The Thermal Storage strategy can significantly increase benefits relative to the Peak Shave strategy, at little incremental cost, if offered to customers with larger (80+ gallon) water tanks in market conditions with a significant price differential between peak and off-peak periods.

- The Fast Response strategy can significantly increase benefits over the other two load control strategies in markets with a need for resources that can quickly ramp load up and down. Ancillary services benefits are less dependent on tank size but very dependent on market conditions, including whether market rules allow demand-side resources to participate in ancillary services markets.

- Uncontrolled heat pump water heaters provide significant economic and environmental benefits in those locations where often-challenging technical factors can be effectively addressed.

- As modeled, using the Peak Shave strategy with HPWHs does not materially improve their economics; alternatively, it would be useful to assess the technical feasibility of providing ancillary services through HPWHs.

- The potential environmental benefits of controlled ERWHs depend heavily on market conditions and the pattern of load curtailment of the water heater. This conclusion is driven in particular by the generation supply mix of the market.

- The net benefits of all of these strategies can be maximized through a portfolio-based approach to promoting the strategies, rather than pursing a single strategy in isolation.

While this study has reached important conclusions about opportunities of water heating strategies, it should be considered a starting point for further detailed exploration of these issues. Specifically, there are a number areas that would benefit from further research as utilities, regulators, policymakers, and industry stakeholders move forward with new water heating initiatives:

Assess techniques for optimizing management and dispatch of the water heaters. The load control strategies modeled in this study were designed to approximately capture the value of various revenue streams (energy, capacity, ancillary services), but with a simple heuristic that does not optimize the water heater's operations. Water heating load could be curtailed to jointly maximize the three revenue streams as well as environmental benefits. A dispatch model could be developed to quantify this value. This would not only provide a better sense for the total maximum potential value of advanced water heating load control but would also provide operational insights that will be useful once the programs are deployed.

Analyze the benefits of "community storage." The strategies modeled in this analysis are assumed to curtail every customer's water heating load exactly the same. With visibility into the load of individual water heaters, the curtailment strategy could be optimized across a portfolio of customers and tailored to individual load profiles to maximize the capability of the program.

Analyze participant benefits. This study only quantified system costs and benefits (also referred to as "societal" cost-effectiveness). Analysis of the bill savings specifically to participants in these programs would also be insightful. If this analysis suggests that customers do not have a strong financial incentive to participate in highly beneficial programs, it would be necessary to explore new mechanisms that would facilitate an economically efficient level of participation (e.g., through time-varying rates or other incentive payments).[61] This analysis could include potential financial benefits to the participant such as reducing demand charges.

Test customer preferences for a range of water heating programs through primary research such as survey-based conjoint analysis. Participation rates included in this analysis are plausible but could be refined through market research. This approach has been successfully used in DR potential studies and helps to highlight the sensitivity of customer participation to incentive structures and payment levels.[62]

Analyze the impact of varying levels of adoption of the water heating strategies on market prices. Particularly as it relates to ancillary services, large levels of adoption could have a significant impact on the market prices. Demand for frequency regulation is limited in most markets and prices would decrease significantly at high levels of participation; accounting for the "depth" of the market would be a useful exercise.

Assess location-specific distribution benefits of the strategies. This analysis assumed a system average avoided distribution capacity cost. Customers could be recruited into water heating load

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[61] This topic will be discussed in more detail in a forthcoming report for the U.S. Department of Energy. Ryan Hledik and Jim Lazar, "Distribution System Pricing for Distributed Energy Resources" (working title), prepared for Lawrence Berkeley National Laboratory, forthcoming. See https://emp.lbl.gov/future-electric-utility-regulation-series for more information.

[62] For example, see Faruqui, Hledik, and Lineweber (2014).

control programs based on their location in order to capitalize on local distribution capacity deferral opportunities, as is currently being explored in New York, California, Hawaii, and other jurisdictions.

Assess strategies to match customers to the controllable water heater best suited to their needs and load profile. Some customers may better suited to a particular water heater control strategy based on their usage profile. Developing methods to match customers to strategies could increase the overall benefits of a portfolio of programs.

Assess market potential for the water heating strategies. It would be valuable to estimate the total potential achievable impact of water heating load control and energy efficiency programs across the U.S., to establish the magnitude of the opportunity. This should be compared to the "depth" of the market for services such as frequency regulation in a more detailed assessment of costs and benefits.

Extend the analysis to other market settings. This analysis focused on benefits in the PJM and MISO markets. Expanding to additional markets with different market rules, such as ERCOT, CAISO, or international jurisdictions, for example, would provide further insight as to the performance of the strategies across a range of market conditions. Due to the nuances of market conditions and rules and their effect on the findings, a detailed economic analysis is recommended for any utility that is considering offering such a program.

Compare the economics of controllable hot water heaters to that of other distributed energy storage options. Controllable water heaters may have unique competitive advantages compared to other distributed energy storage technologies and demand response programs. Understanding the comparative advantages and disadvantages would inform broader demand-side strategy development.

References

ABB, Inc. (2015). Energy Velocity Suite. Data downloaded in June-July 2015.

Battelle (2015). Grid Interactive Water Heater Pilot Demonstration in Oahu, Hawaii. February 23, 2015. Posted at http://aceee.org/sites/default/files/pdf/conferences/hwf/2015/3D-Rehberg.pdf

Bird, Lori, Jaquilin Cochran, and Xi Wang (2014). Wind and Solar Energy Curtailment: Experience and Practices in the United States. NREL Technical Report, March 2014. Posted at: http://www.nrel.gov/docs/fy14osti/60983.pdf

California Public Utilities Commission (CPUC) (2001). California Standard Practice Manual: Economic Analysis of Demand-Side Projects. October 2001. Posted at: http://www.cpuc.ca.gov/nr/rdonlyres/004abf9d-027c-4be1-9ae1ce56adf8dadc/0/cpuc_standard_practice_manual.pdf

Chang, Judy., Johannes P. Pfeifenberger, Kathleen Spees, Matt Davis, Ioanna Karkatsouli, Lauren Regan, James Mashal (2014). The Value of Distributed Electricity Storage in Texas: Proposed Policy for Enabling Grid-Integrated Storage Investments. November 2014. Posted at: http://www.brattle.com/system/news/pdfs/000/000/749/original/The_Value_of_Distributed_Electricity_Storage_in_Texas.pdf

Dyson, Mark, James Mandel, et al. (2015). The Economics of Demand Flexibility: How "Flexiwatts" Create Quantifiable Value for Customers and the Grid. Rocky Mountain Institute, August 2015. Posted at: http://www.rmi.org/electricity_demand_flexibility

U.S. Department of Energy (2015). Residential Water Heaters. Posted at: https://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/27

Electric Power Research Institute (2014). Economic and Cost/Benefit Analysis for Deployment of CEA-2045-Based DR-Ready Appliances.

Energy Information Administration (2009). Residential Energy Consumption Survey. Posted at http://www.eia.gov/consumption/residential/

Energy Information Administration (2015). How is electricity used in U.S. homes? Posted at https://www.eia.gov/tools/faqs/faq.cfm?id=96&t=3

Faruqui, Ahmad, Ryan Hledik, and David Lineweber (2014). Demand Response Market Potential in Xcel Energy's Northern States Power Service Territory. Prepared for Xcel Energy, April 2014. Posted at: https://www.xcelenergy.com/staticfiles/xe/PDF/Regulatory/18-App-O-Demand-Response-Potential-Brattle-Group-Study-January-2015.pdf

Hledik, Ryan and Ahmad Faruqui (2015). Valuing Demand Response: International Best Practices, Case Studies, and Applications. Prepared for EnerNOC, January 2015.

Hledik, Ryan and Jim Lazar. Distribution System Pricing for Distributed Energy Resources (working title). Prepared for Lawrence Berkeley National Laboratory, forthcoming. See: https://emp.lbl.gov/future-electric-utility-regulation-series

Midcontinent ISO (2014). Forecasted LMPs by MTEP Future. Posted at: https://www.misoenergy.org/Planning/TransmissionExpansionPlanning/Pages/MTEPFutures.aspx

Monitoring Analytics (2015a). Marginal Fuel Posting. Posted at: http://www.monitoringanalytics.com/data/marginal_fuel.shtml

Monitoring Analytics (2015b). State of the Market Report for PJM. Volume 2: Detailed Analysis. March 12, 2015. Posted at: http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2014/2014-som-pjm-volume2.pdf.

Newell, Samuel A., Michael Hagerty, Kathleen Spees, Johannes P. Pfeifenberger, and Quincy Liao (2014). Cost of New Entry Estimates for Combustion Turbine and Combined Cycle Plants in PJM. May 15, 2014. Posted at: https://www.pjm.com/~/media/documents/reports/20140515-brattle-2014-pjm-cone-study.ashx.

Northwest Energy Efficiency Alliance (2015). Heat Pump Water Heater Model Validation Study. March 2, 2015. Posted at: https://neea.org/docs/default-source/reports/heat-pump-water-heater-saving-validation-study.pdf?sfvrsn=8

NRECA (2014). Energy Storage - The Benefits of "Behind-the-Meter" Storage: Adding Value with Ancillary Services. May 31, 2014. Posted at: https://www.smartgrid.gov/files/NRECA_DOE_Energy_Storage.pdf

NRECA (2015). Water Heaters for Thermal Energy Storage: Major Cost Benefits but Wider Grid Use Faces Challenges.

Pacific Northwest National Lab (2015). Evaluation of the Demand Response Performance of Large Capacity Electric Water Heaters. March 2015. Posted at: http://labhomes.pnnl.gov/documents/PNNL_23527_Eval_Demand_Response_Performance_Electric_Water_Heaters.pdf

PJM Interconnection (2007). Marginal Losses Implementation Training. Posted at: http://www.pjm.com/sitecore%20modules/web/~/media/training/new-initiatives/ip-ml/marginal-losses-implementation-training.ashx

PJM Interconnection (2011). 2014/2015 RPM Base Residual Auction Results. Posted at: https://www.pjm.com/~/media/markets-ops/rpm/rpm-auction-info/2014-2015-rpm-bra-results-report-addendum.ashx

PJM Interconnection, et al. (2012). Joint Comments of PJM Interconnection L.L.C., National Rural Electric Cooperative Association, American Public Power Association, Edison Electric Institute, and Steffes Corporation to Request for Information RIN 1904-AC78. July 13, 2012. Posted at http://www.eei.org/issuesandpolicy/testimony-filings-briefs/Documents/120713RosenstockDoeWaterHeaterStandards-Joint.pdf

PJM Interconnection (2013). Performance Based Regulation: Year One Analysis. October 12, 2013. Posted at: https://www.pjm.com/~/media/documents/ferc/2013-filings/20131016-er12-1204-004.ashx

Podorson, David. Battery Killers: How Water Heaters Have Evolved into Grid-Scale Energy-Storage Devices. an E Source whitepaper, September 9, 2014. Posted at: https://www.esource.com/ES-WP-18/GIWHs

Potomac Economics (2015). 2014 State of the Market Report for the MISO Electricity Markets. June 2015. Posted at: https://www.misoenergy.org/Library/Repository/Report/IMM/2014%20State%20of%20the%20Market%20Report.pdf

St. John, Jeff (2013). The Water Heater as a Grid Battery, Version 2.0. GreenTech Media, November 8, 2013. Posted at: http://www.greentechmedia.com/articles/read/the-water-heater-as-grid-battery-version-2.0

Steffes, Paul, “Grid Interactive Renewable Water Heating: Analysis of the Economic and Environmental Value.” Posted at: http://www.steffes.com/LiteratureRetrieve.aspx?ID=72241

U.S. Census Bureau (2013). American Housing Survey National Summary Tables. Posted at: http://www.census.gov/programs-surveys/ahs/data/2013/ahs-2013-summary-tables/national-summary-report-and-tables---ahs-2013.html

Appendix A: Memorandum on Water Heater Operations Simulations

DEMAND CONTROLLED ELECTRIC WATER HEATER DIVERSIFIED ELECTRICAL DEMAND STUDY

By
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September 30, 2015

BACKGROUND

This report describes results of a study of electric resistance water heater diversified electrical demand using the WATSIM® detailed water heater computer simulation model, which was specifically developed with capabilities to perform such analysis. This study examined one representative set of climatic/surrounding conditions at one time of year, and studied only standard water heater control plus three demand control strategies. The goal of this study was to produce plots of multi-customer electric water heater diversified electricity demand under the four control approach assumptions, and to further understand impacts of assumed control strategies on households in terms of adequate amounts of hot water being available.

INTRODUCTION

Several attributes are important for desirable electric water heater performance. These include:

1. Efficient, cost-effective, reliable operation
2. Adequate hot water availability
3. Acceptable sound levels, draft/air motion levels and other impacts on users
4. Acceptable impacts on wiring and electric power demand on the utility

In any population of households there are different numbers of people in different households and they use hot water differently. This means that one size water heater does not work for all households.

There are several simple approaches that can be used to increase hot water availability for larger households:

1. Increase water heater setpoint temperature
2. Use a larger water heater (or more than one water heater)
3. Use a mixing valve
4. Use increased heating rates (not usually an option for standard mass-market electric resistance water heaters which tend to be limited to having 4500 Watt elements to avoid overloading standard household wiring circuits intended for powering electric water heaters).

There are basically two types of hot water draws – human uses and machine uses. Humans tend to mix hot and cold water together so that a safe delivery temperature (such as 105 F) is obtained. Machines tend to draw full hot water. Thus if water heater delivery temperature is increased, humans act as mixing valves, adjusting the amount of hot water drawn based on the temperature at which it is delivered, such that a relatively constant amount of hot water energy is consumed in human uses, irrespective of temperature. In comparison machines tend to take fixed volume draws so that they simply consume more hot water energy when hot water delivery temperature is increased.

Automatic temperature mixing valves are used in water heating systems for two reasons. One is to reduce potential exposure to scalding hot water temperatures. The other is to reduce the amount of energy used by machines, thus reducing load on the water heating system when increasing energy storage capability by storing water at higher temperatures.

For purposes of this study we examined three different assumed water heater setpoint temperatures, two different water heater sizes, and presence or absence of a mixing valve, on both normally controlled and load controlled water heaters.

WATSIM®

WATSIM® is a detailed second-by-second full transient analysis computer model of storage water heaters that was developed under the direction of Dr. Carl Hiller while employed by the Electric Power Research Institute (EPRI). Eventually as computer technology evolved WATSIM® has become less fully functional on newer computers because there was no continuing support for upgrades from EPRI. When EPRI eventually discontinued availability of WATSIM® Dr. Hiller purchased rights to WATSIM® and trademarked the name, thereby keeping WATSIM® available to those who need it. WATSIM® is equipped with specific capabilities that allow it to accurately model both single customer and diversified water heater electrical demand, hot water run-outs, effects of changes in water heater design and control features, heat pump water heaters and more.

STUDY METHODOLOGY

WATSIM's® automatic water draw generating code was given draw characteristics for various types of fixtures, and population demographics information, and was used to create a set of 300 different 24 hour hot water draw profiles, representing 300 different household hot water use patterns for the selected day. Since different households are different sizes, not all households would in reality have the same size water heater. To account for this effect in this study we examined three different water heater setpoint temperatures (120 F, 135 F, 160 F), two different water heater tanks sizes (50 gallon and 80 gallon, both EF=0.94), and operation with and without a mixing valve on the tank outlet (set to 120 F if present). Four control strategies were studied; a standard normal thermostat controlled behavior (which we call the uncontrolled case), a load control strategy where power to the water heater was interrupted for 4 hours, from 17:00 to 21:00 (5 to 9 pm) (which we call the 4 hr peak shaving control case), and a load control strategy where power to the water heater was interrupted for 16 hours from 7:00 to 23:00 (7 am to 11 pm). In the latter scenario two subsets of power interrupt strategies were examined. One interrupted power to both elements while the other only interrupted power to the lower element, allowing the upper element to "float", i.e. come on as dictated by its normal thermostat. Entering cold water and surrounding room air temperatures were assumed to be 55 F for all cases. For the load control cases power interrupts were phased in and out over 1 hour periods to reduce the magnitude of the diversified power spike when power was reenabled. A total of 16 different cases were examined, as described below.

Case	Description
50-120 U	Uncontrolled 50 gallon tank set to deliver 120 F
50-135 U	Uncontrolled 50 gallon tank set to deliver 135 F
50-135 U-MV120	Uncontrolled 50 gal. set to 135 F storage temp. but having a mixing valve to limit discharge temp. to 120 F
50-160 U-MV120	Uncontrolled 50 gal. set to 160 F storage temp. but having a mixing valve to limit discharge temp. to 120 F
50-120 Shave4	50 gallon tank set to deliver 120 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
50-135 Shave4	50 gallon tank set to deliver 135 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
50-135 Shave4-MV120	50 gallon tank set to 135 F storage temp. but having a mixing valve to limit discharge temp. to 120 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
50-160 Shave4-MV120	50 gallon tank set to 160 F storage temp. but having a mixing valve to limit discharge temp. to 120 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
80-120 U	Uncontrolled 80 gallon tank set to deliver 120 F
80-135 U	Uncontrolled 80 gallon tank set to deliver 135 F
80-135 U-MV120	Uncontrolled 80 gal. set to 135 F storage temp. but having a mixing valve to limit discharge temp. to 120 F

80-120 Shave4	80 gallon tank set to deliver 120 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
80-135 Shave4	80 gallon tank set to deliver 135 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
80-135 Shave4-MV120	80 gallon tank set to 135 F storage temp. but having a mixing valve to limit discharge temp. to 120 F, with power interrupted for 4 hours from 17:00 – 21:00 (phased in & out over 1 hr)
80-160 16Hr-MV120	80 gallon tank set to 160 F storage temp. but having a mixing valve to limit discharge temp. to 120 F, with power interrupted for 16 hours from 7:00 – 23:00 (phased in & out over 1 hr)
80-160 16HrL-MV120	80 gallon tank set to 160 F storage temp. but having a mixing valve to limit discharge temp. to 120 F, with power interrupted to the lower element only for 16 hours from 7:00 – 23:00 (phased in & out over 1 hr)

RESULTS

Diversified Electrical Demand

Diversified electrical demand from the mix of 300 different households was computed and averaged over 5 minute, 15 minute, and 60 minute intervals. The shorter averaging intervals provide plots that are a bit more jagged (more scatter around the average value), but are in general very similar to the 60 minute (1 hour average) plots, so we present here only the 60 minute moving window (1 hr average computed every 5 minutes) diversified electrical demand results. Figure 1 shows for the 50 gallon tank the lowest and highest diversified electrical demand values that resulted from the uncontrolled and peak shave control cases.[63] We see that diversified electrical demand did not vary much despite changes in tank setpoint or delivery temperature, and that the minimum and maximum values were similar for both the controlled and uncontrolled cases except during and just after the power interrupt control period. Note, however, that as discussed shortly, the hot water run-out results varied substantially even though the diversified electrical demand did not.

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[63] The diversified demand profile of the tank would vary from one market to the next, depending on factors such as the efficiency of tanks and the average temperature of outside water.

Figure 1 shows a typical electric water heater diversified electrical demand profile, with a morning peak of around 1 kW occurring around the 7:00-10:00 am time frame, a smaller noon peak of around 0.6-0.7 kW occurring around the noon-2:00 pm time frame, and an evening peak (uncontrolled cases) of around 0.75-0.85 kW occurring in the 6:00 – 10:00 pm time frame. The peak shaving control reduces the evening peak to zero kW, at the expense of a payback spike which peaks at around 2.0-2.2 kW lasting 2-3 hours beginning shortly after the control interrupt period is over in the 9:00 to 10:00 pm time frame (60 minute phase in period is assumed to reduce magnitude of the spike).

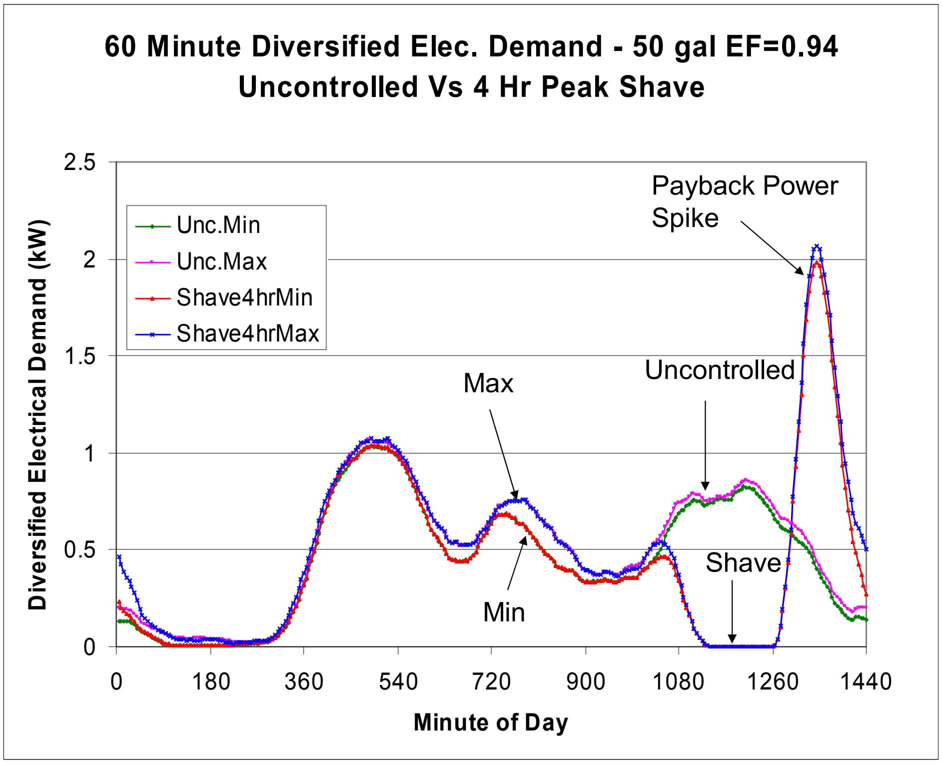


Figure 1: 60 Minute Moving Window Diversified Elec. Demand – 50 gal Tanks

Figure 2 shows for the 80 gallon tank the lowest and highest diversified electrical demand values that resulted from the uncontrolled and peak shave control cases. We see again that diversified electrical demand did not vary much despite changes in tank setpoint or delivery temperature, and that the minimum and maximum values were similar for both the controlled and uncontrolled cases except during and just after the power interrupt control period. We also note that the diversified electrical demand plots for the 50 and 80 gallon tanks end up being very similar. However, hot water run-out results were quite different for the different cases as discussed below.

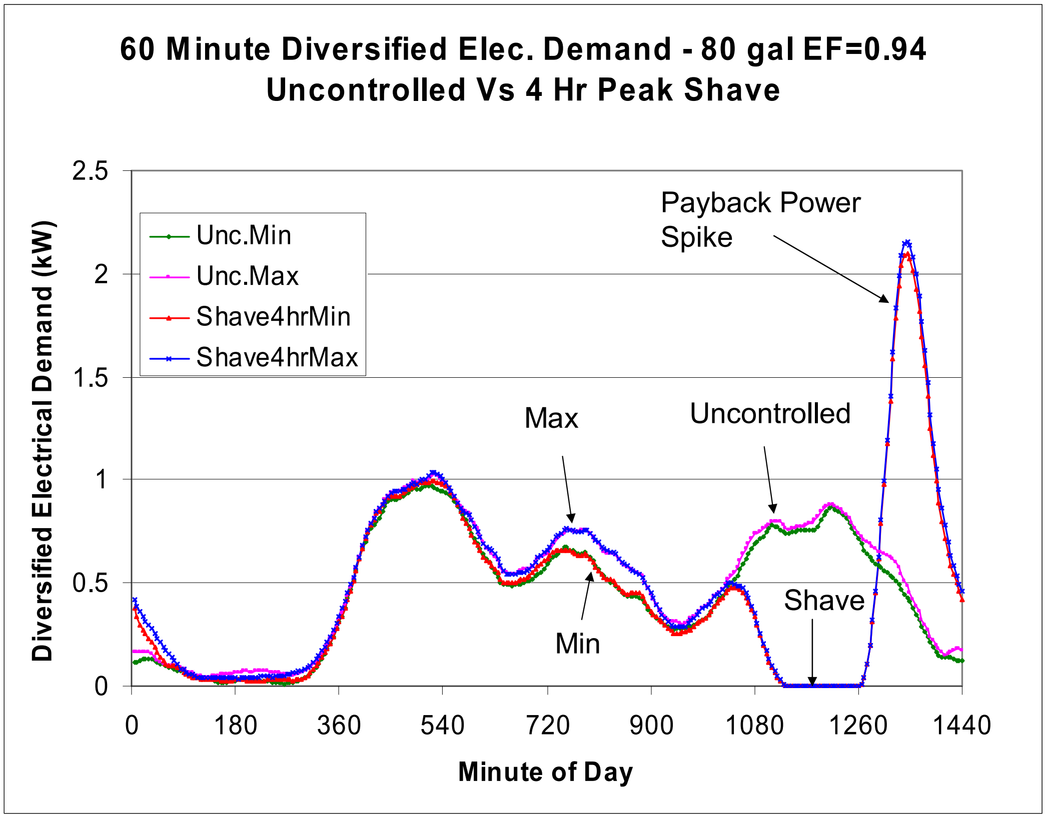


Figure 2: 60 Minute Moving Window Diversified Elec. Demand – 80 gal Tanks

Figure 3 shows how the diversified electrical demand of the two 80 gallon tank 16 hour power interrupt scenarios compare to that of an uncontrolled 80 gallon tank set to store at 135 F, with all three cases having a mixing valve set to 120 F. As can be seen, there is zero electrical demand for most of the day with the full 16 hour power interrupt, with a payback power spike of around 3.8 kW occurring in the early morning hours. In comparison, interrupting power to only the lower element produces a similar payback power spike, but also results in small afternoon diversified power use due to upper element operation. However, as discussed next, interrupting power to both elements results in an unacceptable number of hot water run-outs whereas allowing the upper element to come on as necessary provides an acceptably low number of run-outs. It is worthwhile to note that the 3.8 kW payback power spike represents all water heaters running simultaneously except households where no one was home that day, which is why the spike is not 4.5 kW.

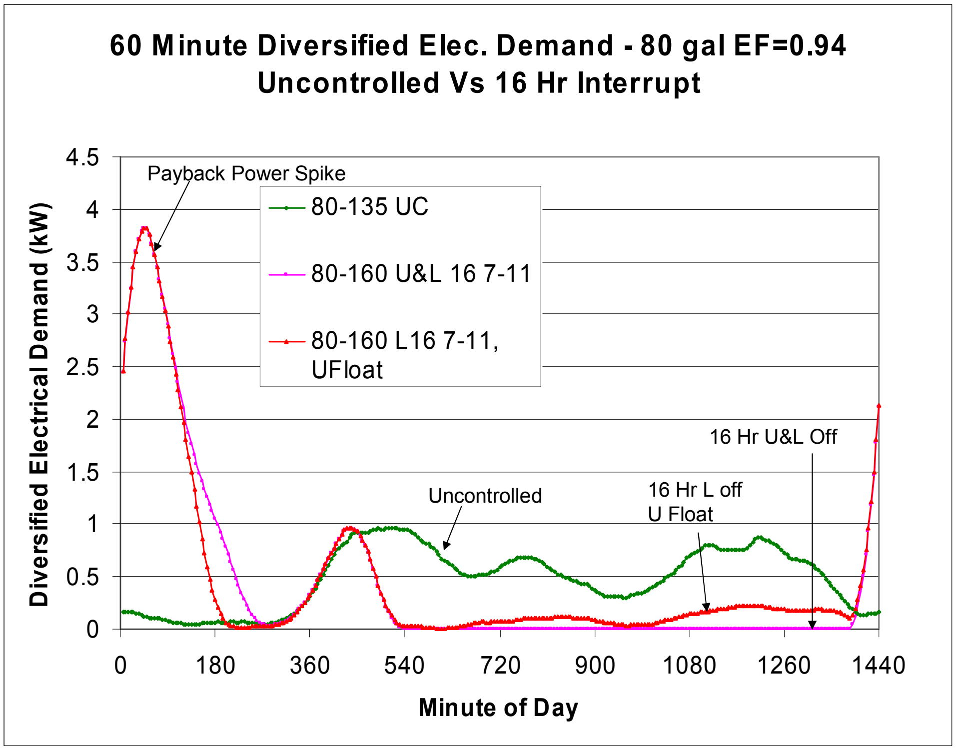


Figure 3: 60 Minute Moving Window Diversified Elec. Demand – 80 gal Tanks-16 Hr Interrupt

Hot Water Run-Outs

Since WATSIM® accurately tracks tank outlet temperature we are able to quantitatively estimate the frequency, duration, and extent of hot water run-outs. We report here a simplified version of those findings, simply reported as the percentage of households that experienced "severe" hot water run-outs. In this case we have defined "severe" hot water run-outs as the energy equivalent of delivering more than 5 gallons per day at temperatures lower than 105 F.

As a general rule, if a water heater or control approach causes more than about 3% of households to experience severe hot water run-outs, the approach is assumed to be unacceptable. Figure 4 shows that giving all households 50 gallon water heaters set to deliver 120 F significantly exceeds this threshold, with more than 20% of households experiencing severe hot water run-outs, even in the uncontrolled case. What this suggests is that those households need to set the temperature higher (possibly accompanied by a mixing valve) or use a larger tank.

Figure 4 shows that for the uncontrolled case the larger households with more demanding hot water use can still use a 50 gallon storage tank if they set the temperature up to 135 F or above, and they work even better if an outlet temperature limiting mixing valve is also attached. However, when the 4 hour peak shaving power interrupt is imposed in the evening, setting the temperature up to 135 F, even if a mixing valve is also used, still exceeds the threshold for acceptable run-outs when using a 50 gallon tank. In order for the 50 gallon tank to provide acceptable hot water run-out performance with the 4 hour evening power interrupt, the setpoint temperature must be raised up to the 160 F range, and a mixing valve MUST be used.

Alternatively, as shown in figure 4, households with higher hot water use can obtain acceptably low hot-water run outs by using an 80 gallon tank, and that tank can still be set to relatively low temperatures. With 80 gallon tanks 120 – 125 F works in the uncontrolled case, but a somewhat higher temperature setting such as 130-135 F is required to avoid excessive hot water run-outs for those larger households under the 4 hour evening power interrupt period.

Figure 4 also shows that interrupting power for 16 hours to both the upper and lower elements of an 80 gallon tank set to store water at 160 F and equipped with a mixing valve to limit output temperature to 120 F results in 10.7 percent of households having severe hot water run-outs. Under this control scenario, basically what happens is that any household that uses more than tank volume during the day runs out of hot water. For 80 gallon tanks actual tank volume is 72 gallons. In comparison, interrupting power to only the lower element and leaving the upper element to come on as dictated by its normal thermostat works well, with only 3% of households experiencing severe hot water run-outs. This comes at the price of slightly higher afternoon diversified electrical demand – 0.22 kW vs zero for the full interrupt case and vs 0.87 kW for the uncontrolled case.

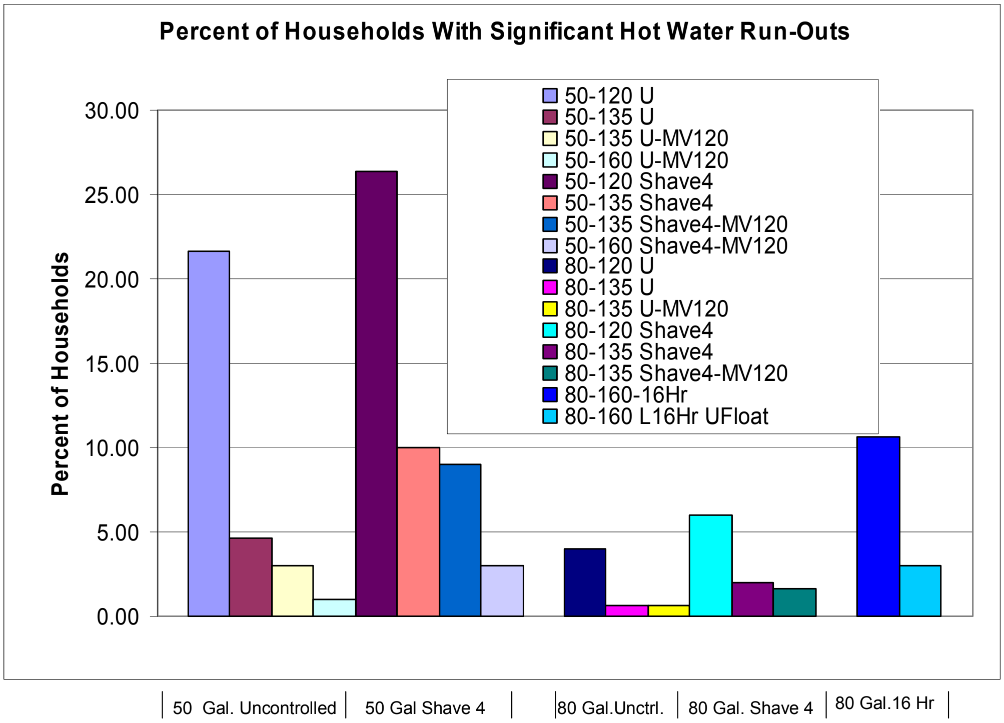


Figure 4:Hot Water Run-Out Comparisons

CONCLUSIONS OF DIVERSIFIED ELECTRICAL DEMAND ANALYSIS

It is not reasonable to assume that all electric water heater customers can maintain an acceptable supply of hot water while using the same size tanks set to the same relatively low hot water delivery temperatures such as 120 F. Even with no added power interrupt devices, some households will need to set smaller water heaters, such as 50-55 gallon units, to temperatures in the 135-140 F range or will need larger tanks such as 80 gallon units set to 120-125 F in order to obtain acceptable amounts of hot water, due to differences in hot water needs across households.

In order to obtain acceptable amounts of hot water when even small periods of power interrupt, such as 4 hours, are imposed, a large percentage of households (on the order of 10-25% in this study) using 50-55 gallon water heaters will need to be set to store water at temperatures in the 160 F range. They must also be equipped with mixing valves to prevent scalding and reduce amount of hot water used by machines. Alternatively, those households could use 80 gallon water heaters set to deliver temperatures in the 130-135 F range.

When attempting to do long periods of power interrupt such as 16 hours, even if 80 gallon tanks are used set to store water at 160 F, a potentially unacceptable number of hot water run-outs will occur. However, if the upper element is left uncontrolled, it comes on for those households that need it and provides adequate hot water, at the expense of slightly higher afternoon diversified electrical demand than the full interrupt approach, but still significantly lower than the full uncontrolled case. Alternatively, for those households that would experience hot water run-outs with an 80-gallon tank and a 16-hour interruption period, a larger tank size (e.g., 100 gallons) would help to address the risk of a hot water shortage.

Remember too that this study was performed with an assumed 55 F entering cold water temperature. This is basically summer-time entering cold water temperature in northern climate locations. In winter entering cold water temperatures in many northern climate locations drop to the 32-35 F range, meaning that either higher setpoint temperatures, larger tanks, or a reduced interruption period may be required in northern climates during winter months.

Appendix B: Additional Detail on Assumptions and Methodology

General Methodological Assumptions

- Premise-level peak demand reductions are grossed up by a reserve margin requirement of 16.2% (based on PJM reserve margin in 2014/15 base residual auction) to produce system-level avoided generation capacity costs.
- Water heating load impacts are grossed up by an average line loss estimate of 8% in all hours.
- The discount rate used to annualize costs is assumed to be an after-tax WACC of 8%.
- The maximum load of an ERWH is 4.5 kW.
- Inlet water temperature is assumed to be consistent with Great River Energy's average conditions.
- No adjustment is made to HPWH operations to account for variation in ambient air temperature across markets.
- Capacity benefits of the 50-gallon Peak Shave strategy are derated by 10% to account for operational limitations (e.g., constrained dispatch window).

Participation Rate Assumptions

- HPWHs are less than 1% of the electric water heating market. We assume that a focused program designed to promote adoption of this technology could increase adoption to 5% for "baseline" customers with a 40- to 50-gal ERWH. Note that these customers have a tank size that is below the 55-gal threshold, above which the new EPA standard would require HPWH for all non-grid connected electric water heaters.
- Residential direct load control programs of various types have commonly achieved enrollment rates of 20% of eligible customers. In some cases, such as Xcel Energy's air-conditioning direct load control program, participation among eligible customers has reached 50%. Great River Energy's water heating load control program enrollment rate is roughly 40% of eligible customers (i.e., those with electric water heating). We have conservatively assumed a 20% participation rate for all WH load control options in our analysis.
- Customer preferences for the different load control options (Peak Shaving, Thermal Storage, Fast Response) will depend on the specific characteristics of those programs and likely vary across the programs. Customers who are willing to incur frequent interruptions in return for a larger incentive payment may be more likely to enroll in a Thermal Storage program, whereas more risk averse customers who would only tolerate occasional interruptions in return for a smaller financial reward might prefer the Peak Shave option. The Fast Response option provides the largest financial upside but would also require that the customer adopt more expensive control equipment. Due to lack of

data on customers' relative preferences for these program types, we have assumed identical participation levels across the three programs when offered in isolation. When offered as a portfolio of options rather than in isolation, we assume that customers would tend to gravitate more toward the programs offering higher financial incentives (i.e., Thermal Storage and Fast Response)

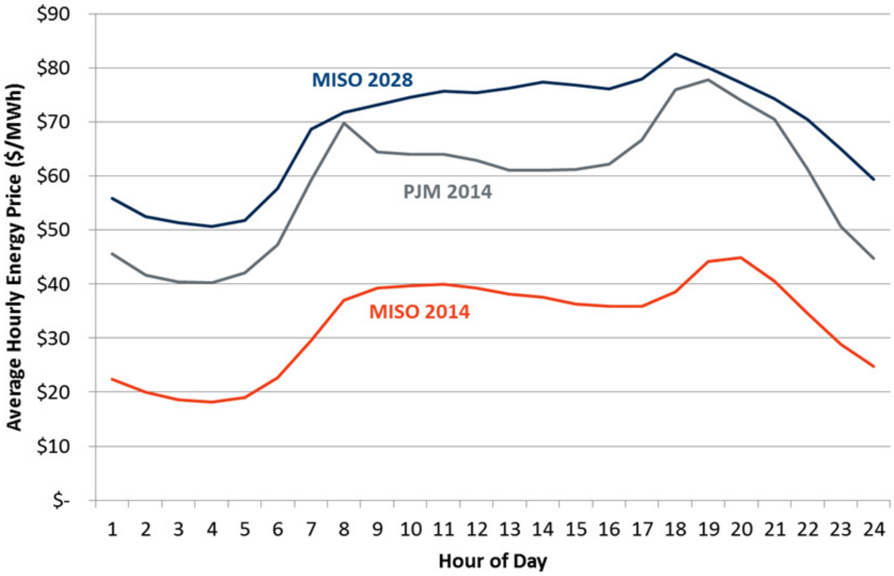
- Total enrollment in some form of water heating program is expected to be higher when a portfolio of options is offered, because customers will have choices that best suit their needs. Market research has found that when a menu of demand response programs is offered to customers (e.g. time-of-use rates, critical peak pricing rates, and A/C direct load control), total enrollment significantly exceeds the enrollment of any single program if offered in isolation
- These assumptions are illustrative and should be explored further through primary market research and survey-based conjoint analysis.

CO_2 Pricing in the MISO 2028 Market Scenario

One of the assumptions in MISO's MTEP modeling that underlies the MISO 2028 market scenario is a CO_2 price of $50/ton. That CO_2 price is implicitly embedded in the energy price for that scenario. In our analysis, we separately identify and report the direct cost or benefit of a change in CO_2 emissions associated with the water heating strategies under this assumption. To do this, we first estimate the net change in marginal CO_2 emissions associated with each strategy by identifying the marginal fuel in each hour and comparing this to the hourly change in load attributable to the given water heating strategy relative to the baseline uncontrolled 50-gallon ERWH. We then multiply the net change in CO_2 emissions by the CO_2 price of $50/ton to arrive at the total increase or decrease in emissions cost associated with that water heating strategy over the study year. These values are added or subtracted from the energy cost savings for the MISO 2028 scenario and reported in the footnotes to each of the figures in the report which summarize the total net benefits of a water heating strategy in the MISO 2028 scenario. With this approach, we have not attempted to completely "unwind" the impact of the CO_2 price on the generation supply mix. We have simply isolated the direct impact of a change in CO_2 emissions from the water heating strategies.

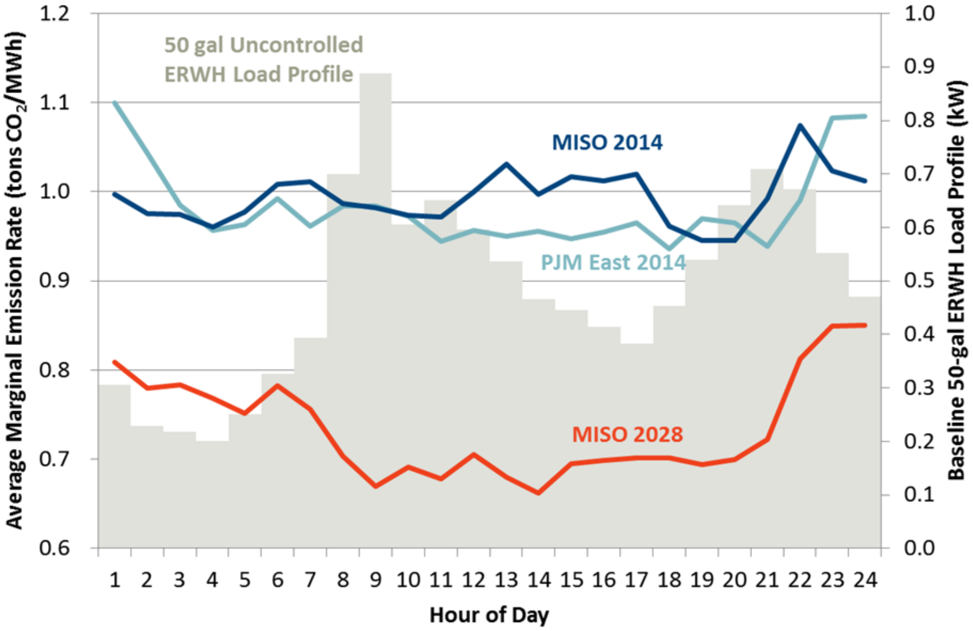
Average Energy Price Profiles

The following is the average hourly energy price profile for each of the three market scenarios modeled in our analysis. Note that the MISO 2028 price profile implicitly reflects the impact of the CO_2 price modeled in that scenario.



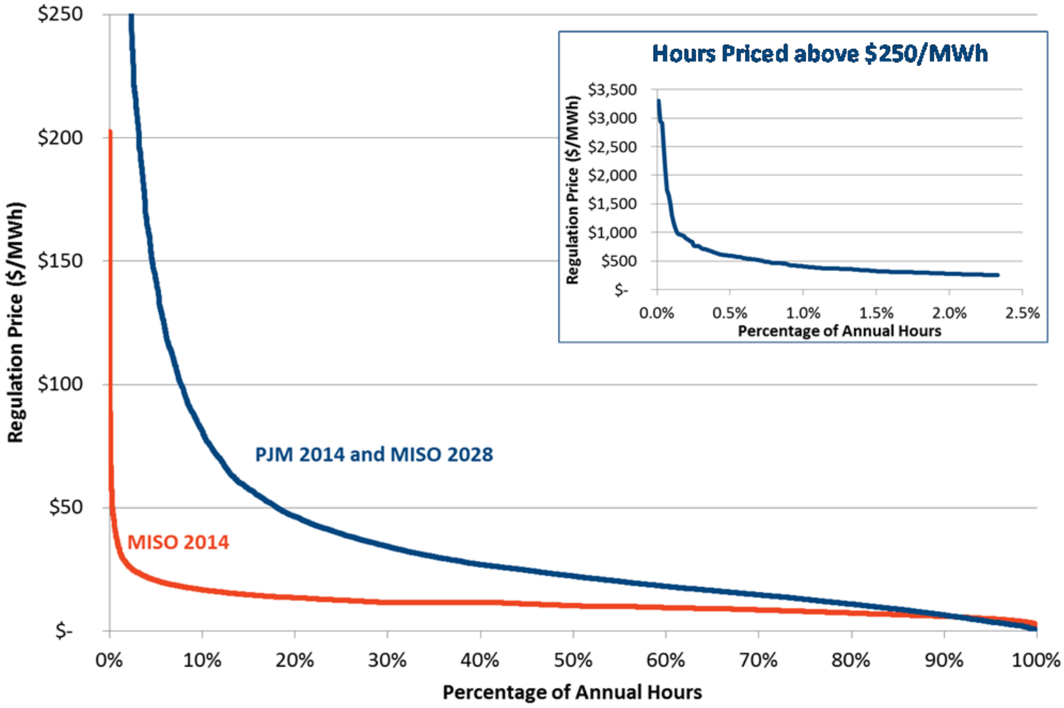
Marginal Emissions Profiles

The following are the average hourly marginal emissions profiles of the three market scenarios. They are estimates based on publicly available information where available.



Frequency Regulation Price Duration Curve

The following are price duration curves for frequency regulation prices included in the three market scenarios in our analysis.



Appendix C: Detailed Results

PJM 2014 Market Scenario

		Load Pattern		Annual incremental costs per participant					Annual avoided costs (i.e., benefits) per participant					
		Peak-coincident demand (kW per WH)	Annual energy consumption (kWh per WH)	Water Heater	Other Equipment	Installation	Incentives & program costs	Total annual cost	Generation capacity	T&D capacity	Energy	Ancillary services	Total annual benefits	Annual net benefits
Baseline*	***50 gal***	***0.51***	***4,251***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	$0.00	***$0.00***
ERWH: Peak Shave	50 gal	0.00	4,251	$0.00	$11.68	$17.52	$3.50	$32.71	$28.37	$14.86	$2.50	$0.00	$45.73	$13.02
	80 gal	0.00	4,335	$11.68	$11.68	$17.52	$3.50	$44.40	$31.52	$16.51	-$2.70	$0.00	$45.33	$0.94
ERWH: Thermal Storage	50 gal	0.00	4,251	$0.00	$23.37	$23.37	$3.50	$50.24	$28.37	$14.86	$21.98	$0.00	$65.21	$14.98
	80 gal	0.00	4,335	$11.68	$23.37	$23.37	$3.50	$61.92	$31.52	$16.51	$70.40	$0.00	$118.43	$56.51
ERWH: Fast Response	50 gal	0.00	4,251	$0.00	$58.41	$23.37	$3.50	$85.29	$28.37	$14.86	$21.98	$181.87	$247.08	$161.79
	80 gal	0.00	4,335	$11.68	$58.41	$23.37	$3.50	$96.97	$31.52	$16.51	$49.61	$171.68	$269.32	$172.36
HPWH: Uncontrolled	50 gal	0.24	2,009	$84.94	$0.00	$0.00	$0.00	$84.94	$14.97	$7.84	$138.12	$0.00	$160.93	$75.99
HWPH: Peak Shave	50 gal	0.00	2,009	$84.94	$11.68	$17.52	$3.50	$117.65	$28.37	$14.86	$140.62	$0.00	$183.85	$66.20

Note:
For reference, the total system-level cost (capacity + energy) of operating the baseline 50-gal ERWH in this market scenario is $303 per year.
This estimate is likely lower than the total cost to the customer of operating the water heater, which would be based on the all-in retail electricity rate.

MISO 2014 Market Scenario

		Load Pattern		Annual incremental costs per participant					Annual avoided costs (i.e., benefits) per participant					
		Peak-coincident demand (kW per WH)	Annual energy consumption (kWh per WH)	Water Heater	Other Equipment	Installation	Incentives & program costs	Total annual cost	Generation capacity	T&D capacity	Energy	Ancillary services	Total annual benefits	Annual net benefits
Baseline*	***50 gal***	***0.46***	***4,251***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	$0.00	***$0.00***
ERWH: Peak Shave	50 gal	0.00	4,251	$0.00	$11.68	$17.52	$3.50	$32.71	$0.65	$14.86	$2.50	$0.00	$18.00	-$14.71
	80 gal	0.00	4,335	$11.68	$11.68	$17.52	$3.50	$44.40	$0.72	$16.51	-$0.47	$0.00	$16.76	-$27.64
ERWH: Thermal Storage	50 gal	0.00	4,251	$0.00	$23.37	$23.37	$3.50	$50.24	$0.65	$14.86	$14.50	$0.00	$30.00	-$20.24
	80 gal	0.00	4,335	$11.68	$23.37	$23.37	$3.50	$61.92	$0.72	$16.51	$52.66	$0.00	$69.88	$7.96
ERWH: Fast Response	50 gal	0.00	4,251	$0.00	$58.41	$23.37	$3.50	$85.29	$0.65	$14.86	$14.50	$93.84	$123.84	$38.55
	80 gal	0.00	4,335	$11.68	$58.41	$23.37	$3.50	$96.97	$0.72	$16.51	$40.62	$85.06	$142.90	$45.93
HPWH: Uncontrolled	50 gal	0.22	2,009	$84.94	$0.00	$0.00	$0.00	$84.94	$0.34	$7.84	$78.88	$0.00	$87.06	$2.12
HWPH: Peak Shave	50 gal	0.00	2,009	$84.94	$11.68	$17.52	$3.50	$117.65	$0.65	$14.86	$81.38	$0.00	$96.88	-$20.77

Note:
For reference, the total system-level cost (capacity + energy) of operating the baseline 50-gal ERWH in this market scenario is $164 per year.
This estimate is likely lower than the total cost to the customer of operating the water heater, which would be based on the all-in retail electricity rate.

MISO 2028 Market Scenario

		Load Pattern		Annual incremental costs per participant					Annual avoided costs (i.e., benefits) per participant					
		Peak-coincident demand (kW per WH)	Annual energy consumption (kWh per WH)	Water Heater	Other Equipment	Installation	Incentives & program costs	Total annual cost	Generation capacity	T&D capacity	Energy	Ancillary services	Total annual benefits	Annual net benefits
Baseline*	***50 gal***	***0.46***	***4,251***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	***$0.00***	$0.00	***$0.00***
ERWH: Peak Shave	50 gal	0.00	4,251	$0.00	$11.68	$17.52	$3.50	$32.71	$44.05	$14.86	$2.50	$0.00	$61.40	$28.69
	80 gal	0.00	4,335	$11.68	$11.68	$17.52	$3.50	$44.40	$48.94	$16.51	-$1.98	$0.00	$63.47	$19.07
ERWH: Thermal Storage	50 gal	0.00	4,251	$0.00	$23.37	$23.37	$3.50	$50.24	$44.05	$14.86	$16.55	$0.00	$75.45	$25.22
	80 gal	0.00	4,335	$11.68	$23.37	$23.37	$3.50	$61.92	$48.94	$16.51	$70.01	$0.00	$135.45	$73.54
ERWH: Fast Response	50 gal	0.00	4,251	$0.00	$35.05	$23.37	$3.50	$61.92	$44.05	$14.86	$16.55	$181.87	$257.32	$195.40
	80 gal	0.00	4,335	$11.68	$35.05	$23.37	$3.50	$73.60	$48.94	$16.51	$52.13	$171.68	$289.26	$215.66
HPWH: Uncontrolled	50 gal	0.22	2,009	$84.94	$0.00	$0.00	$0.00	$84.94	$23.23	$7.84	$119.07	$0.00	$150.14	$65.20
HWPH: Peak Shave	50 gal	0.00	2,009	$84.94	$11.68	$17.52	$3.50	$117.65	$44.05	$14.86	$119.07	$0.00	$177.97	$60.32

Note:
For reference, the total system-level cost (capacity + energy) of operating the baseline 50-gal ERWH in this market scenario is $356 per year.
This estimate is likely lower than the total cost to the customer of operating the water heater, which would be based on the all-in retail electricity rate.