Consumer Strategies for Controlling Electric Water Heaters under Dynamic Pricing

Chong Hock K. Goh and Jay Apt

***Abstract*—Electricity used to heat water represents 9% of residential demand in the USA and can be 40% in other countries. Hourly residential use of hot water is often anti-coincident with the peak generation of electricity, presenting an opportunity for reducing consumer costs under dynamic pricing during the afternoon generation peak. We have examined the effects of three strategies on customer costs under dynamic pricing: timed power interruption (long used by certain utilities), a price-sensitive thermostat, and a double period setback timer. Systems which lower the water temperature set points are as economical as power interruption systems, and result in higher minimum water temperature. Our model predicts that a setback thermostat will keep the tank water warmer than a load interruption timer with very similar electricity use. The setback thermostat and the more complex price-sensitive thermostat achieve similar water temperatures and consumer savings.**

***Index Terms*—Economics, Home appliances Power systems, Power system economics, Power system planning, Power system operations, Power system reliability.**

I. Introduction

DEMAND for electricity reaches a peak near 4 PM in many control areas, such as the California ISO, whose load curve for a July day is shown in Fig. 1. The peak demand often can be 25% above the average demand during the day and 70% above the minimum [1]. Reducing the peak load can significantly reduce consumer costs when the consumer is being charged for the true cost of peak power.

Heating of residential water by the 41 million electric water heaters in the United States out of 107 million total residential water heaters [2] is responsible for 8.7% of residential electricity use [3]. The largest reported residential load fraction is 40%, in South Africa [4]. Periods of peak use of water occur in the morning and early evening (see Fig. 1, a similar profile measured over a 4-month period by [5], and the 15,000-home data of [6]).

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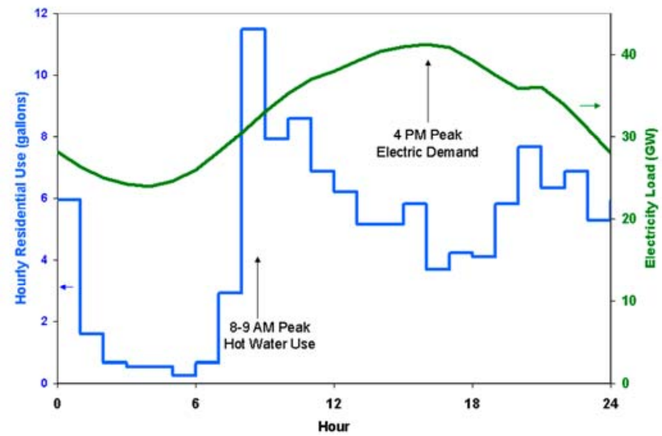

Fig. 1. Hourly USA residential hot water usage (stepped curve, per [20]) and representative electric load curve for all sectors (smooth curve, from California ISO, July 16, 2004).

The average household hot water draw at the 4 PM (hour 16) peak of overall electric demand is one-third of that at the 8-9 AM peak of hot water use. Reference [7] presents data from one U.S. utility on hourly electricity energy use for residential water heaters in both summer and winter. Reference [6] gives similar curves for South Africa. Since hot water use is low in the afternoon, residential hot water use has been identified as a candidate for electricity peak reduction based on pricing that reflects the high hourly costs of delivering electricity at peak use times [8]. In addition, since thermal loss causes the thermostat to command the heating element on (a heater cycle) once or twice during the low-use period after midnight, minor energy savings may be achieved by heater control during this period.

Detroit Edison began in 1934 using timers to interrupt power to residential water heaters for four continuous hours per day, selected to coincide with the daily electric system load peak [9]. In 1968, the timers were replaced by FM radio control, with 200,000 heaters switched in ten blocks under control of the system operator (still constrained by tariff to a maximum of four hours off time per day). 95.5% of residential water heater customers chose to participate, in exchange for a 26% water heater rate reduction. System costs for the radio control system averaged $275 per customer (2005 dollars). After switchover to the radio control system, the utility found that they commanded interruptions most frequently to reduce the use of oil-fired peak generators or imported power. Utility cost of electricity for heating the water after the heaters were re-enabled were generally two-thirds of the peak costs.

Wisconsin Electric Power Company installed power line carrier load management of water heaters in Milwaukee and surrounding areas beginning in 1979 [10]. By 1985, 100,000 heaters were in the program. The load management rate tariff permitted heaters to be switched off for up to eight hours per day. In practice, heaters were de-activated for no more than three consecutive hours or four total hours in one day. Peak load reduction of 2% was achieved, with oil-fired peakers being replaced by gas shoulder plants and coal baseload units. The increase in system load when the heaters were re-enabled was generally three times the average shed load, but was managed by staggering groups of heaters.

Carolina Power & Light Company conducted an experiment interrupting power to 200 residential water heaters as a load control mechanism in the winters of 1979-80 and 1980-81 [11]. Using this field data, they modeled the effects of controlling 200,000 residential heaters, finding that peak system demand could be reduced by 3%. A significant spike in load was observed after the heaters were switched back on; optimal control strategies involved staggered control of groups of heaters.

Florida Power & Light uses power line communication in a load control program for 712,000 customers. FPL currently pays residential customers monthly incentives of $3.50 for controlling water heaters and attributes 1 GW of peak demand reduction to the load control program [12].

If water heater loads are simply cut off at particular periods, the utility may experience system stability issues. This was a subject of research in the early 1980s, as reviewed in [5]. Here we compare this technique to two others: lowering the set-point of the water heater at specific times (as in a HVAC thermostat) and changing the set-point in response to dynamic prices via a price-sensitive thermostat communicating with the load serving entity.

In a recent report, the California Energy Commission Demand Response Committee [8] estimated that dynamic pricing (real-time pricing or time-of-use pricing are forms of dynamic pricing based on the real-time market prices) could achieve "short-term peak reduction …between 4.7 and 24 percent of California's estimated peak load by 2013. The residential and small commercial customer share of these estimated peak savings range from roughly 15 to 25 percent with balance coming from medium to large commercial and industrial customers. The long-term peak reduction is estimated to be 3.4 to 15 percent of the projected 2013 peak load."

A few U.S. utilities have used residential real-time pricing, notably GPU (beginning in 1997), AEP, and Gulf Power. In the GPU pilot program, residential summer peak use was 2 kW in a control group and 1.5 kW in the participating group, with larger peak shaving during "critical price" events [13], [14]. California's Statewide Pricing Pilot (SPP) program tested several forms of real-time pricing in 2003 and 2004. A strong argument for dynamic pricing is provided in [15]: "consumer underestimates of hot-water cost, especially for electric resistance water heaters, suggest that we do not currently even enjoy the conservation effects which market forces would provide."

Most previous work on water heater electricity use reduction has been undertaken from the point of view of the utility. However, consumers have adopted devices such as setback thermostats for heating and air conditioning as a means of reducing energy bills even without tariff incentives or dynamic pricing. Here we examine the potential savings to the residential consumer from both price-sensitive thermostats and setback thermostats for residential electric water heating, finding that similar savings can be realized by both methods. Although both methods are feasible, implementation of the setback thermostat method requires fewer infrastructure changes, and presents an near-term attractive opportunity for adoption by manufacturers and customers.

II. Model

In order to investigate these strategies, we have developed and verified a simple model of a residential electric water heater (Fig. 2).

In this model, the temperature of the mass of water increases or decreases evenly without incorporating thermal layers. Commercial electric water heaters have 2 heating elements (one near the top and the other at the bottom, with only 1 heating element active at a time); this model heater has only a single heating element.

Reference [16] describes a more complex simulation, incorporating two heating elements and heat transfer among six layers of water within the tank. As we discuss below, our results agree closely with theirs. We also have run our model using the U.S. Department of Energy EnergyGuide test procedure for commercial water heaters [17]. Using that test protocol, we calculated the total energy used per year, and compared these results to the EnergyGuide ratings of two commercial 50-gallon water heaters, and two commercial 80-gallon water heaters. As discussed in the section below describing model validation, our results showed agreement to within 0.6 to 4.3 percent for several validation tests.

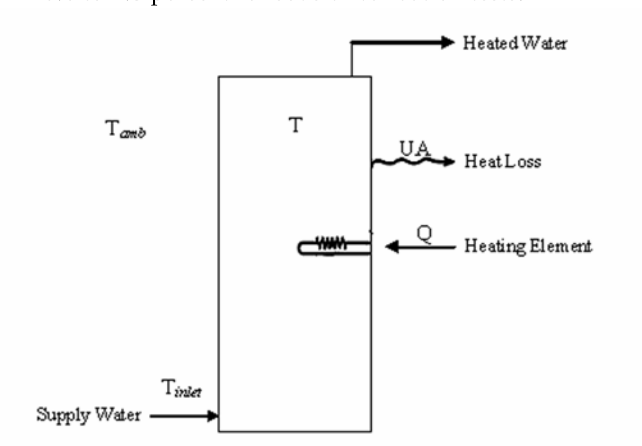

Fig. 2. Water heater model

The temperature change of the water is governed by [18], [19]:

$$M \cdot SH_w \cdot \frac{dT}{dt} = UA \cdot (T_{amb} - T) + Q \quad (1)$$

where

M = mass of water in the tank (lb)

SH_w = specific heat of water (BTU/lb/°F)

T = Temperature of the water in the tank (°F)

t = time (hr)

UA = standby heat loss coefficient • area of the storage tank (BTU/°F/hr) (see [17] p. 26014 for definition)

T_{amb} = Ambient temperature (°F)

Q = rate of heat input to tank from the heater (BTU/hr); zero when the heater is off.

The modeled heater has insulation which affects the UA of the heater. The UA factor governs the rate at which the water cools. Commercially available heaters with 2 inch insulation have an approximate UA factor of 4, and heaters with 3 inch insulation have an approximate UA factor of 2.5. The UA values are not directly proportional to the inverse of the insulation thickness due to end effects and penetrations.

As heated water leaves the tank, the tank is refilled with water from the cold water inlet supply. The temperature of the water after a withdrawal of hot water and addition of inlet water is:

$$T_{new} = \frac{T_{curr} \cdot M_{curr} + T_{inlet} \cdot M_{inlet}}{M_{curr} + M_{inlet}} \quad (2)$$

where

T_{new} = temperature of water after inlet water is added to current water in the tank

T_{curr} = current temperature of the water (after water draw)

T_{inlet} = cold water inlet temperature

M_{inlet} = mass of water from cold water inlet

M_{curr} = mass of water left in the tank (after water draw).

The rated tank volume for some commercial hot water heaters is somewhat larger than the measured volume. We have used the rated volume in this work.

The model was run with a time step of 0.01 hour, for a specified length of time (normally 10 days). For the 24-hour EnergyGuide test profile validation runs discussed below, the time step was decreased to 0.001 hour. The ASHRAE water use profile [20] (or the EnergyGuide test profile [17]) was consulted to determine the withdrawal at each time step. When the heater was off, the temperature of the tank was calculated with equations 1 (with Q = 0) and 2. If the temperature was below the lower thermostat set point, the heater was switched on, and the temperature increased per equation 1 until a time step when temperature reached the upper set point and the heater was switched off.

III. Model Validation Tests

We performed two types of validation testing on the model. We first ran the test profile used in the EnergyGuide tests for electric water heaters [17]. The parameters used were: ambient temperature 67.5°F, inlet water temperature 60°F, initial temperature of the tank's water 135°F, thermostat high cutoff temperature 140°F, and low cutoff temperature 130°F.

We compared our results modeling four commercial heaters sold by Sears to their published EnergyGuide energy use. All commercial models studied are equipped with two 5500 watt heating elements, with only one in use at a time; our model used a single 5500 watt element. The first heater (Kenmore model 32756, Sears item 04232756000) has 2.5 inch thick insulation and a 50 gallon capacity. The EnergyGuide test energy usage is reported as 4879 kWh/year. Running our simulation program with the same parameters and procedures used in the Department of Energy test protocol, the energy usage by our simulated heater is 4912 kWh/year, within 0.7% of the published rating. The only parameter adjusted to achieve a match was the heat loss factor; all others were set at the midrange of the test protocol values as listed above. The best match (values reported above) was with a heat loss factor 3.6 Btu/°F/hr. Using the same heat loss factor, we simulated a similar 80 gallon model with 2.5 inch insulation (Kenmore model 32986, Sears item 04232986000); the EnergyGuide usage is 4721 kWh/year, while our simulated heater's usage is 4750 kWh/year (within 0.6% of the reported rating).

We also tested the model against two higher efficiency Sears models with 3 inch insulation. We used the same parameters as above, except that the heat loss factor was set to 2.5 Btu/°F/hr to model the thicker insulation. For the 50 gallon Kenmore model 32154 (Sears item 04232154000), the reported EnergyGuide usage is 4622 kWh/year. Our simulated heater's wattage usage was 4423 kWh/year (4.3%). For the similar 80 gallon model with 3 inch insulation (Kenmore model 32184, Sears item 04232184000), the reported EnergyGuide usage is also given as 4622 kWh/year. Our simulation (with the parameters unchanged except for the water volume) gave 4708 kWh/year, within 1.9% of the reported rating. These comparisons are summarized in Table I.

TABLE I
COMPARISON OF SIMULATED AND MEASURED ENERGYGUIDE VALUES

Sears Kenmore Product	Sears Kenmore EnergyGuide Values (a) (kWhr/yr)	Simulation Result (b) (kWhr/yr)	Difference (b-a)/a
Model 32756 (50 gallon, 2.5” insulation)	4879	4912	+ 0.7%
Model 32986 (80 gallon, 2.5” insulation)	4721	4750	+ 0.6%
Model 32154 (50 gallon, 3” insulation)	4622	4423	- 4.3%
Model 32184 (80 gallon, 3” insulation)	4622	4708	+ 1.9%

Fig. 3 shows the temperature of the water in the tank during a simulation of the 24-hour EnergyGuide test for the 50-gallon model with 2.5 inch insulation. The test protocol calls for six water draws at hourly intervals at the start of the test period, after which the heater is allowed to maintain temperature within its temperature control band without water draws.

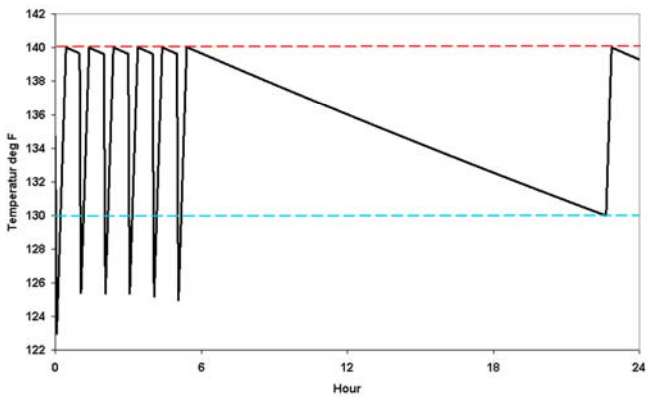

Fig. 3. Simulated 24 hour EnergyGuide test. The solid line is the modeled temperature of the water in the heater tank, which decreases during the hourly water draws mandated in the first six hours of the test. Water temperature also decreases due to thermal leakage. The heater is switched on when the lower set point (130 °F) is reached, and off at the upper set point (140). Simulation test conditions: Kenmore model 32756, 50 gallon capacity, 2.5" insulation, ambient temperature 67.5 °F, inlet water temperature 60 °F, 5500 watt heater, initial tank water temperature 135 °F, heater cut-in temperature 130 °F, heater cut-out temperature 140 °F, heat loss factor (UA) 3.6 BTU/ °F/ hr.

Second, we used our model to calculate thermal efficiency as defined in [16], using their operations schedule A and constant volume hot water draws. Simulating their 82 gallon "Tank A" and using parameters given in their Table 4, we calculate a thermal efficiency of 0.801, in agreement to within 2.6% of their value of 0.822.

Comparison of our model's results to the EnergyGuide ratings and to the model of [16] show agreement to within the experimental variability noted in [21].

IV. Modeling Four Strategies

A conventional water heater thermostat has a lower (cut-in) and upper (cut-out) limit, providing a control band around the desired temperature. The model permits the selection of the upper and lower limits, and allows investigation of the results of three mechanisms by which those limits are controlled:

(1) No changes to the limits. The model heater maintains the temperature of the water as in Fig. 4, with the frequency of heater cycles affected by the ASHRAE schedule water draw.

(2) Power to the water heater is turned off at specific times. Interruption control of this type has been used in most of the load control programs discussed above. Fig. 5 shows the results for the model heater when power is interrupted from six hours, beginning at 1 PM.

(3) The limits are controlled by a two-period timer with selectable periods and selectable change to the lower limit (the upper limit is a fixed offset above the lower, by 5 degrees in our simulations) as in Fig. 6. This is similar to double setback thermostats routinely used for residential heating and air conditioning control.

(4) The limits are controlled in response to the price of electricity. The controller is given the range of daily price variation, and adjusts the lower limit so that it reaches its minimum value when the price is at a maximum. We have modeled a dynamic price sensitive thermostat by varying the target water temperature (T_{target}) with the price of electricity (P), and fixing the deadband (difference between the high and low setpoints), as shown in Fig. 7:

$$T_{target} = T_{\max} - \left(\frac{P-P_{\min}}{P_{\max}-P_{\min}}\right)\times(T_{\max}-T_{\min}) \qquad (3)$$

where T_{max} is the desired water temperature at low electricity price (for example, 120 °F), T_{min} is the minimum temperature the consumer will accept (100 °F in our work here), and P_{max} and P_{min} are the maximum and minimum electricity prices during the day.

We used a summer Massachusetts wholesale price schedule, scaled to give the 2002 average retail price for the 48 contiguous states of 8.41 ¢/kWh. The maximum scaled price is 12.39 ¢/kWh at 4-6 PM, while the minimum is 6.34 ¢/kWh at 4-5 AM. The model calculates the cost of electricity at each time increment, noting whether the heater is on (as controlled by the thermostat) and the price at that time (selected either as a flat rate or as a dynamic price).

For consistency, we adopted a 5500 watt heater element, a ± 2.5 degree temperature control band, and the EnergyGuide test protocol parameters for ambient temperature (67.5 °F) and inlet water temperature (60 °F). We note that inlet water temperature has a strong influence on the energy used, and that opportunities for savings may exist in regions where the cold water pipes are not buried to a depth which minimizes seasonal change. As an example, increasing the inlet temperature from 45 to 55 °F decreases energy use by 12% in a simulation using the residential hot water use profile of Fig. 1, the 50 gallon, 2.5 inch insulation model, and a 120 °F set point.

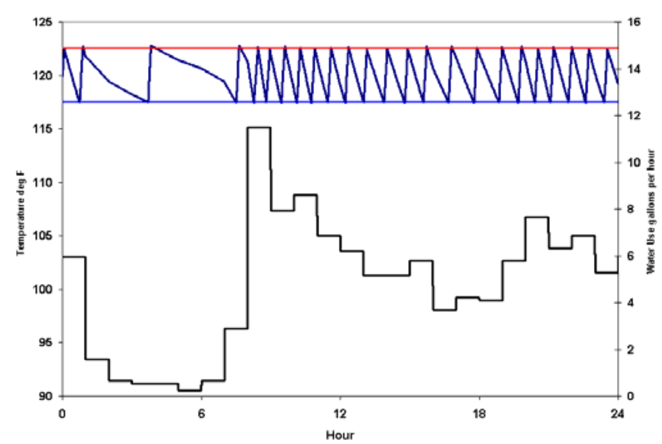

Fig. 4. Conventional thermostat. water temperature, with high and low thermostat limits shown on the left scale. hourly water use in gallons shown on the right scale. High use causes frequent heater cycles.

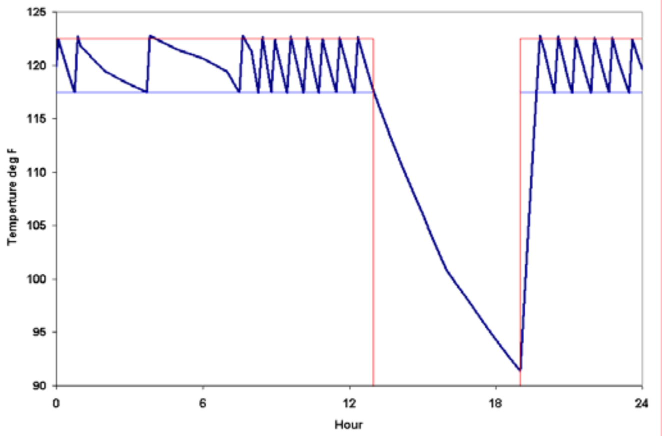

Fig. 5. Power is interrupted to the water heater from 1-7 PM. Same water use profile as in Fig. 4.

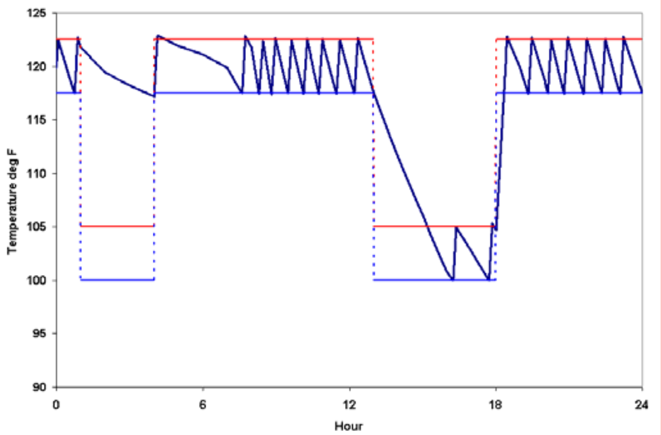

Fig. 6. Two-period setback thermostat. Same water use profile as in Fig. 4.

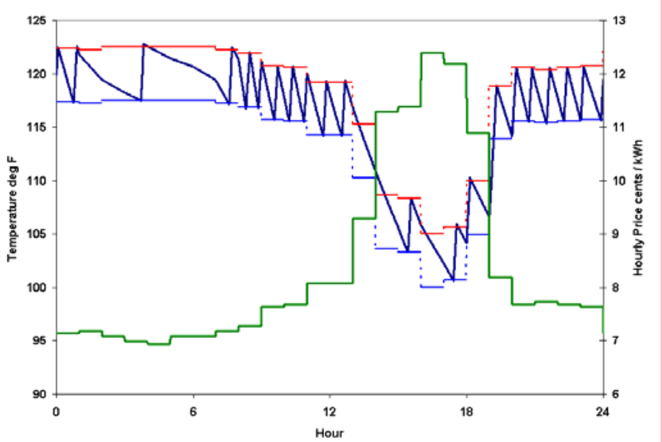

Fig. 7. Dynamic price-sensitive thermostat. Hourly price shown on right scale. Setpoints adjusted per equation (3). Same water use profile as in Fig. 4.

V. Results

Consumers may adopt strategies for reducing their electric water heating cost which are rational under existing flat rate tariffs. We quantified the effects of three of these: adjustment of the conventional water heater thermostat, purchase of well-insulated heaters or after-market insulation, and use of a thermostat which lowers the set point. In areas which employ dynamic pricing, consumers may wish to use setback timed thermostats or closed-loop price-sensitive thermostats (which change the set point in response to price signals received from the load-serving entity). Most earlier work has considered timed power interruption to the heater. This work examines set point adjustment to a minimum level set by the consumer.

We have run simulations with both 120 and 140 °F set points. Significant scalding risks exist at tap discharge temperatures greater than 120 °F [22], [23]. A few states require set points in the 120-125 degree range. For example, §704.06 of the Wisconsin State Code requires a residential landlord to set water heater temperature no higher than 125 °F. Our model runs show that for all four water heaters described previously, setting the thermostat to 120 °F uses 75% of the energy required to maintain a 140 °F set point. In high-price states such as New York, the yearly savings would be $315, greater than the purchase price of a 50 gallon electric water heater. Most water heater thermostats are not calibrated, so outlet temperature must be measured with a device such as a household meat thermometer to adjust the set point. This strategy is effective and can be important system-wide. The lower temperature range does not greatly increase the risk of bacterial growth; the OSHA Technical Manual notes that the optimum growth range for *Legionella pneumophila* bacteria is 95-115 °F and that stagnant water with amoebae and protozoa is generally required to promote growth [24].

Our simulation shows, as expected, that the cost of running the water heater increases linearly with values of UA. The simulation predicts that the difference in yearly operating cost between an 50 gallon model with UA of 3.6 and one with UA of 2.5 at the 8.41 ¢/kWh average residential price at a set point of 140 °F is $21.90. The retail capital price difference between the two models is $30. Many models are warranted for 12 years, so the extra insulation is a rational purchase with a 2 year pay back period.

As discussed previously, some utilities have interrupted power to water heaters, and homeowners can purchase timers to interrupt power to the heater. Multi period setback thermostats are common in household heating and air conditioning control systems; they change set points rather than interrupting power. A similar control might be built into water heaters. Table II shows that the yearly savings of the two strategies is predicted to be very similar, but the power interruption device allows the water temperature to fall to levels which consumers may find less desirable than a minimum temperature that they select with a setback thermostat.

The reduction of electricity use during peak periods by the timer or setback thermostat can be important for electric system operators. System margins of electric capacity above demand are generally no more than 20%, and can be much less on hot summer afternoons or in specific areas. The estimate for the 2004 July capacity margin was 6.9% in the New York Independent System Operator (ISO) region and 8% for the eastern Wisconsin and Illinois region covered by the Mid-Atlantic Interconnected Network [25]. The achieved peak load reduction of 2% in the Wisconsin water heater program is a significant fraction of total reserve margin, and reductions of this order can be crucial when equipment fails.

Dynamic pricing has been proposed as a means to reduce peak load by having consumers pay the lower cost of running baseload units at off-peak periods and the higher cost of peaking units during the few hundred hours per year these units run (e.g., [8]). We have used our model to investigate the cost and performance of strategies under the time-of-day price curve of Fig. 7. Table III gives the results for a 50 gallon water heater equipped with a conventional thermostat, a power interruption timer, a setback thermostat, and an adaptive price-sensitive thermostat responding to prices communicated from the load-serving entity. All strategies under a dynamic price tariff require interval meters which record the use of power at small time steps. A price-sensitive thermostat requires communication of prices to the consumer and thermostat in real time, or seasonally-averaged prices which are loaded into the controller periodically.

In order to quantify the cost and performance under an hourly price tariff, we have modeled prices in New York City. The New York ISO publishes day-ahead prices for each hour in 15 geographic markets [26]. Since the day-ahead markets represent roughly 90% of the power traded, their prices are representative of wholesale prices. We compiled the hourly data for New York City for 2003. We added a fixed 8 ¢/kWh to these wholesale costs for distribution, billing, and tax, to get an estimate of hourly residential prices under a dynamic pricing tariff (the average yearly wholesale cost was 6.37 ¢/kWh, so the average residential cost for the year for New York City customers under our assumptions would be 14.37 ¢/kWh, a good match to bills obtained from customers in New York City). We then used our model to calculate the cost and performance of strategies under such a tariff with these New York City prices. Table IV gives the results for a 50 gallon water heater equipped as for Table III.

One component of California's Statewide Pricing Pilot (SPP) program (Critical Peak Pricing – Fixed) allowed rates to rise to 78 ¢/kWh during peak times on up to 15 days of the year. While complexities of the tariff make this program difficult to model, savings at least as large as those in Table III are likely.

VI. Conclusion

Use of a setback thermostat reduces annual electricity use by 320 kWh (at either set point). If we estimate that the sales price of such a device will be roughly the same as that for a low-end heating setback thermostat ($30), the payback period under a fixed tariff of 8.41 ¢/kWh would be one year.

Under a fixed-price tariff, load interruption timers or setback thermostats reduce average electricity used by the heater by 5-8%, saving $30 annually using the U.S. average residential price. Our model predicts that a setback thermostat will keep the tank water 9 to 16 °F warmer than a load interruption timer with very similar electricity use. Both can have significant benefits for system operators, since the load reduction during peak use time can be a significant fraction of system capacity margin.

The introduction of two-way communication with the electric utility to convey dynamic prices to thermostats requires significant infrastructure changes. Although interval meters are being introduced, price communication to the appliance appears to be some ways off. However, most of the benefits to both the consumer and load-serving entity would be realized by the adoption of setback thermostats, with use schedules which can be altered from a factory default by the consumer to fit their needs.

Acknowledgment

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TABLE II
COST AND PERFORMANCE UNDER A FIXED ELECTRIC PRICE TARIFF

	120 ±2.5 °F set point		140 ±2.5 °F set point	
Strategy	**Yearly Cost @ 8.41 ¢/kWh**	**Lowest Tank Temperature**	**Yearly Cost @ 8.41 ¢/kWh**	**Lowest Tank Temperature**
Conventional Thermostat	$554	117.4 °F	$740	137.4 °F
Interruption Timer Schedule A	$522	94.3 °F	$698	107.3 °F
Interruption Timer Schedule B	$510	91.4 °F	$683	103.2 °F
Setback Thermostat Schedule A	$528	99.9 °F	$712	119.9 °F
Setback Thermostat Schedule B	$520	99.9 °F	$705	119.9 °F

50 gallon water heater with UA=3.6 (2.5 inch insulation). Fixed electric price tariff of 8.41 ¢/kWh. Both the interruption timer and the setback thermostat have been programmed for lower electricity use, in Schedule A from 1-4 AM and 1-6 PM. Schedule B extends the second period to 7 PM, and might be used by consumers without large early evening hot water consumption. The interruption timer removes power from the heater during those times. The setback thermostat lowers the set point by 20 °F during those periods.

TABLE III
COST AND PERFORMANCE UNDER A DYNAMIC ELECTRIC PRICE TARIFF

	120 ±2.5 °F set point		140 ±2.5 °F set point	
Strategy	**Yearly Cost**	**Lowest Tank Temperature**	**Yearly Cost**	**Lowest Tank Temperature**
Conventional Thermostat	$554	117.4 °F	$740	137.4 °F
Interruption Timer Schedule A	$516	94.3 °F	$693	107.3 °F
Interruption Timer Schedule B	$468	91.4 °F	$628	103.2 °F
Setback Thermostat Schedule A	$529	99.9 °F	$715	119.9 °F
Setback Thermostat Schedule B	$497	99.9 °F	$687	119.9 °F
Dynamic Thermostat	$498	100.6 °F	$683	120.6 °F

Dynamic electric price tariff which averages 8.41 ¢/kWh (Fig. 7 and note 2 above). Both the interruption timer and the setback thermostat have been programmed for lower electricity use, in Schedule A from 1-4 AM and 1-6 PM. Schedule B extends the second period to 7 PM. The interruption timer removes power from the heater during those times. The setback thermostat lowers the set point by 20 °F during those periods. The dynamic thermostat lowers the set point by 20 °F during the daily price maximum, and by an amount proportional to the difference between the daily maximum and minimum price at other times. Same water heater parameters as Table II.

TABLE IV
COST AND PERFORMANCE UNDER A DYNAMIC TARRIF USING HOURLY PRICES IN NEW YORK CITY DURING 2003

	120 ±2.5 °F set point		140 ±2.5 °F set point	
Strategy	**Yearly Cost**	**Lowest Tank Temperature**	**Yearly Cost**	**Lowest Tank Temperature**
Conventional Thermostat	$988	117.4 °F	$1320	137.3 °F
Interruption Timer Schedule A	$932	94.3 °F	$1257	106.5 °F
Interruption Timer Schedule B	$918	91.4 °F	$1226	102.5 °F
Setback Thermostat Schedule A	$939	100.0 °F	$1274	119.9 °F
Setback Thermostat Schedule B	$924	100.0 °F	$1258	119.9 °F
Dynamic Thermostat	$925	104.9 °F	$1257	121.8 °F

Dynamic electric price tariff adds fixed costs of 8 ¢/kWh to the actual wholesale hourly cost of power in New York City during the 8760 hours of 2003 (Fig. 8). Same water heater parameters as Table II. All timers and thermostats operate as described for Table III.

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