Demand Response as a Substitute for Electric Power System Infrastructure Investments

Jason W Black (jwblack@mit.edu)
Massachusetts Institute of Technology

Abstract – This paper investigates the system-wide implications of regulatory policies to promote demand response as a substitute for investments in system capacity (generation, transmission, and distribution). Investments in demand response technologies, such as smart thermostats for thermal energy storage, have the potential to improve the efficiency of operations and investments in the electric power system. Reducing the magnitude of demand fluctuations will allow the utilization of the generation, transmission, and distribution systems to be increased and the levels of ancillary voltage and frequency support and reserves reduced. An analysis of the long term effects of demand response on electricity pricing and generation investment is modeled. This analysis enables a general comparison of the potential for avoided costs in generation, transmission, and distribution that could be expected from active regulatory support of demand response investments.

Introduction

This paper investigates the potential for demand response to provide a substitute for capacity investments. Large scale implementation of demand response is modeled to determine the potential impact on capacity investments. The paper focuses on demand response at the residential level, which is typically discounted in terms of its potential size and perceived cost effectiveness. This paper attempts to present a case for the potential for residential demand response. Section 1 of the paper outlines the potential of demand response to reduce peak loads via thermal storage or load shifting. Section 2 contains an example illustrating the potential for thermal storage. Section 3 briefly explores the issues associated with implementing large scale demand response. Section 4 presents the results from simulations to determine the effects of large scale demand response on long term generation capacity. Section 5 illustrates the potential for demand response to substitute for investments in transmission capacity. Section 6 gives a brief overview of secondary benefits from demand response. Section 7 explores areas for future research.

I. Potential for Thermal Storage and Load Shifting

Innovations in control and communications technologies enable the creation of relatively low cost demand response schemes. A significant portion of peak demand can be shifted using these technologies given the proper regulatory and market structures. Past studies of the potential for demand response typically involved studies of consumer reaction to real time or time of use pricing without including the technologies to facilitate demand response. Several utilities currently have successful demand response programs that demonstrate the potential for peak shaving. The majority of these programs focus on large consumers. There is significant potential for peak shaving amongst smaller, residential consumers, however, that could be realized with the proper incentive schemes.

Electricity demand is indirect demand. Consumers do not actually demand electricity itself, but the services provided by equipment that uses electricity. Electricity demand can be differentiated by demand for power and demand for energy. Demand for power is instantaneous, while demand for energy is not. Energy based demand can be utilized as a storage mechanism for electric power. In addition, the services provided by equipment which demands power rather than energy are not time dependent in many cases.

A sub category of power demand consists of deferrable load. Washers, dryers, dishwashers, and possibly electric ovens are examples of appliances that have deferrable load. Consumers often are not concerned with the exact times that such appliances run, as long as it is within a certain interval. This presents an opportunity for deferring the power consumption by these appliances from peak to off peak time periods – especially if programmable controls are available to automate the deferral. Although these appliances typically make up a small portion of the total residential load due to their intermittent usage, they do consume significant amounts of power while running and therefore offer the potential for significant peak shaving whenever they can be shifted to off peak consumption.

Energy Based load consists of air conditioners, refrigerators, water heaters, and electric space heaters. These provide service based on thermal transfer (heat or cooling). As such, consumers are indifferent to the actual time that this equipment runs, as long as the temperature remains within a certain range. By intelligently controlling consumption, the desired temperature range can be utilized as a thermal storage medium, and therefore as an indirect electricity storage method.

Energy based load accounts for nearly 50% of total household consumption. This represents a very large potential for load shifting in order to reduce peak demand by utilizing thermal storage. Air conditioning accounts for over 20% of household electricity usage in the United States. Air conditioning load is also highly peak coincident, since summer peaks are almost entirely caused by air conditioning load. "Residential and commercial air conditioning load represent at least 30% of the summer peak electricity loads". [2]

Refrigeration accounts for over 10% of household electricity usage [2]. The load pattern of a refrigerator involves cycling over short time periods, on the order of minutes, which is relatively smooth between hours. This load profile is a result of the thermal characteristics of refrigerators and the desire for minimizing temperature deviations.

The storage time for a refrigerator is therefore too short to adequately allow for inter-hour load shifting. It is possible, however, to utilize for short term load reductions such as frequency control or possibly for VAR compensation. Refrigerators may also be integrated into protections schemes – they could "trip" much like circuit breakers in response to voltage sags and prevent higher level outages.

Thermal storage programs typically involve the use of chillers to create ice during off-peak hours that is then melted during peak hours to offset air conditioning load. [8] Chillers are installed only at larger load sources due to costs and economies of scale. Although it is possible that this technology could be expanded to the mass consumer market, it would involve the installation of significant equipment at the household level. A simpler method of thermal storage that can be adopted at the household level utilizes the internal air temperature of the home to store energy. By intelligently cycling air conditioners, while maintaining temperatures within a comfort zone instead of at a single setting, significant load can be shifted from peak hours. Such a scheme can also be applied to electric water heaters and electric heat.

II. Thermal Storage Example

The following example illustrates the potential for load shifting from thermal storage using air conditioning. The example utilizes a simple control scheme, based on the methodology outlined in the paper by Constantopoulos, Schweppe, and Larsen [1] and the optimization method developed by Daryanian [10]. Day ahead pricing data from the PJM system from July 8, 2003, along with Temperatures from Philadelphia, Pa are used as inputs to the model. The objective is to control the output of a residential air conditioning system for optimal cost savings. The result provides the potential economic savings from employing such a control scheme, as well as the resultant reductions in peak load power usage. Hourly pricing at the retail level is necessary for consumers to benefit from this thermal storage scheme.

The consumer's objective is to minimize the cost of air conditioning while maintaining the indoor air temperature within a certain range.

$$Min_e C_{ac} = \sum_i P_i * q_i \qquad (1)$$

s.t..

$$0 \le q_i \le q^{\max}$$

$$T^{\min} \le T_i \le T^{\max}$$

where:

$T^{min} = T^{ideal} - d$

$T^{max} = T^{ideal} + d$

d = Acceptable temperature deviation

q_i - energy (kWh) consumed for air conditioning in hour i.
P_i - price of electricity ($/kWh) in hour i.
q^{max} - Maximum power output of Air conditioner

The hourly household temperature, T, is determined by:

$T_{i+1} = \varepsilon\, T_i + (1- \varepsilon)(T^o - \eta * q_i / A)$ (2)

TABLE 1. Parameters and Values of Residential AC Control Model

Variable	Value	Description
T_0	75	Initial temperature (°F)
η	2.5	Efficiency of AC (COP)
q_i		Power output of AC in hour i
q_{max}	3.5	Maximum power output of AC (KW)
E	0.93	System inertia
T^o		Outside Temperature (°F)
A	0.14	Thermal Conductivity (KW/°F)
T_d	75°	Desired household Temp (°F)
D	2°	Maximum acceptable Temperature Deviation (°F)

**Parameter values from [1 and 5]*

The optimization assumes that temperature variations within ± 2° F of the thermostat set point do not result in loss of consumer utility – this deviation is well within the 7° F comfort zone established by the ASHRAE Handbook (See Figure below).

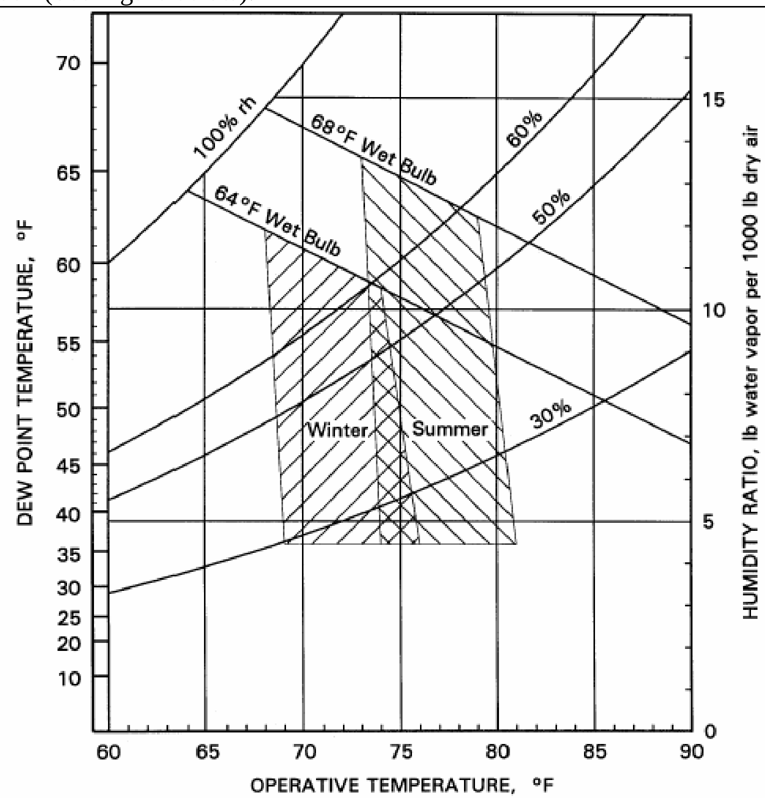


Fig. 5 ASHRAE Summer and Winter Comfort Zones
(Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

Table 2 compares the results of applying a load control scheme to the AC versus the base case of allowing the AC to run on a single thermostat setting. It is assumed that the consumer is indifferent to indoor temperature fluctuations between 73° and 77°F (T^{ideal} = 75°, d = 2°)

Table 2. Normal vs. Controlled Air Conditioning Schemes

Date	8-Jul-03		Normal Cycling			Load Control		
Hr	Price ($/MWh)	Temp (outside)	Temp (inside)	Output (KWh)	Cost (mils)	Temp (inside)	Output (KWh)	Cost (mils)
1	$ 32.43	76	75.0	0.09	2.92	75.1	0.00	0.00
2	$ 24.23	78	75.0	0.31	7.51	75.3	0.00	0.00
3	$ 22.34	77	75.0	0.20	4.47	75.4	0.00	0.00
4	$ 21.43	75	75.0	0.00	0.00	75.4	0.00	0.00
5	$ 21.41	75	75.0	0.00	0.00	73.0	3.35	71.65
6	$ 23.45	74	74.9	0.00	0.00	73.0	0.09	2.11
7	$ 30.55	75	74.9	0.00	0.00	73.0	0.20	6.11
8	$ 39.65	77	75.0	0.10	4.16	73.0	0.40	15.86
9	$ 49.66	79	75.0	0.40	19.86	73.0	0.60	29.80
10	$ 58.45	82	75.0	0.70	40.92	73.0	0.90	52.61
11	$ 68.55	85	75.0	0.99	67.86	73.0	1.19	81.57
12	$ 82.31	84	75.0	0.90	74.08	73.0	1.10	90.55
13	$ 92.16	85	75.0	0.99	91.24	73.5	0.53	48.98
14	$ 105.32	87	75.0	1.21	127.44	74.4	0.00	0.00
15	$ 113.13	89	75.0	1.41	159.51	75.4	0.00	0.00
16	$ 118.23	88	75.0	1.30	153.70	76.3	0.00	0.00
17	$ 126.77	86	75.0	1.10	139.44	77.0	0.00	0.00
18	$ 118.94	86	75.0	1.10	130.84	77.0	0.90	107.05
19	$ 93.85	86	75.0	1.10	103.23	77.0	0.90	84.46
20	$ 83.79	85	75.0	0.99	82.95	77.0	0.79	66.19
21	$ 79.89	83	75.0	0.79	63.11	77.0	0.59	47.13
22	$ 69.03	83	75.0	0.79	54.53	77.0	0.59	40.73
23	$ 48.95	81	75.0	0.60	29.37	77.0	0.40	19.58
24	$ 43.72	81	75.0	0.60	26.23	75.0	3.26	142.39
			Totals -	15.67	1,383.38		15.79	906.77

Figure 2 below compares the controlled versus uncontrolled air conditioning consumption. The peak reduction in consumption is clear from the graph. Figure 3 illustrates the effect of pre-cooling to enable the reduction in peak consumption. When using thermal storage, the air is cooled (energy is stored) to the minimum temperature just prior to off peak hours and then allowed to rise during the peak hours (storage is discharged).

Figure 2. Comparison of Controlled to Uncontrolled Consumption

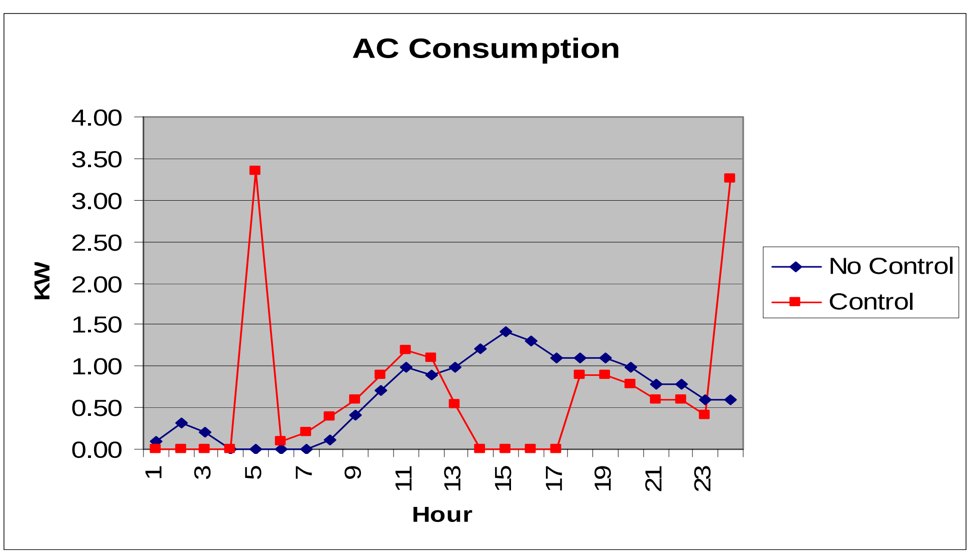
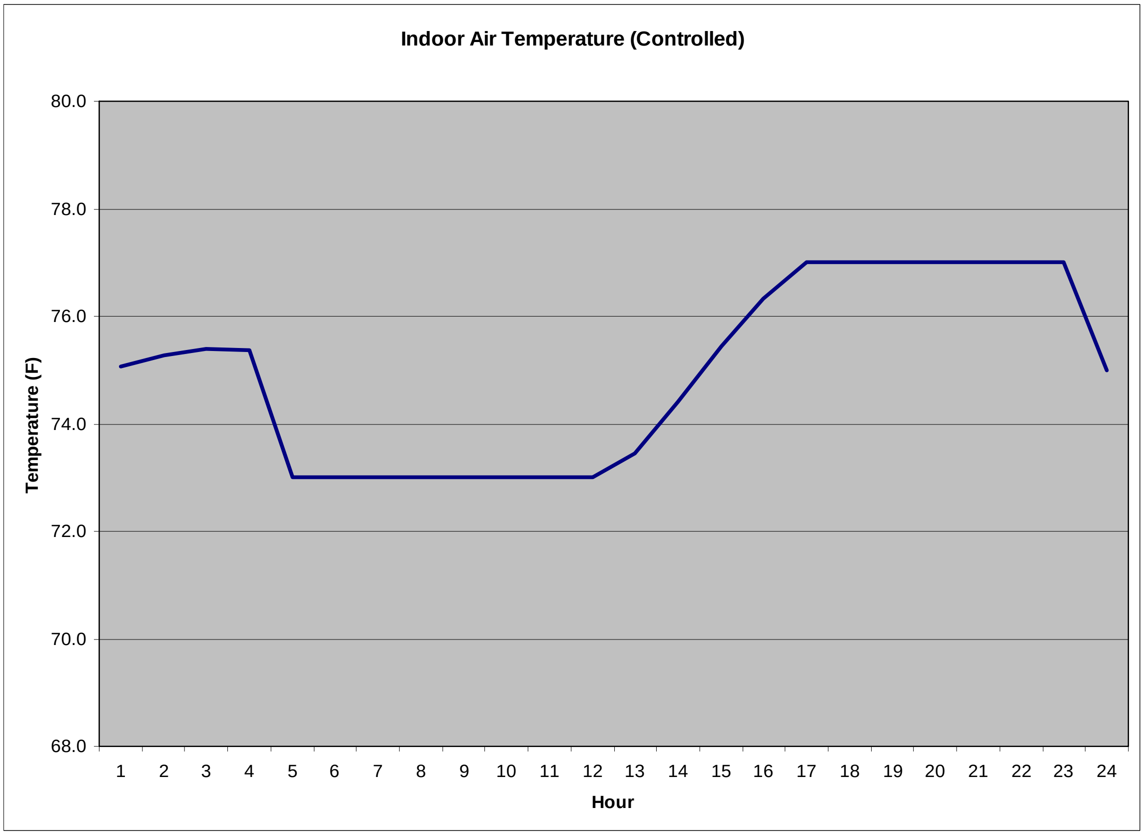


Figure 3. Indoor Air Temperature for Controlled Thermal Storage



As shown, during the five highest price hours of the day (hours 14-18), an 85% reduction in peak demand for air conditioning can be achieved by load shifting without moving outside the maximum temperature deviation. There is, however, a moderate increase in consumption in the hours before and immediately after the peak hours; with the highest consumption at beginning and end of the control period. The overall energy consumption increases very slightly, but the customer reduces their costs by over 33% for the day. The thermal storage control scheme enables significant savings and peak reductions while maintaining comfort. The system wide effects of large scale implementation of thermal storage are explored in subsequent sections.

III. Implementation

Implementing demand response requires investments at both the system and the customer levels. At the system level, the communications, metering, and billing infrastructure is necessary to facilitate a demand response program. Several utilities have invested in this infrastructure with the costs being included in their rate bases. Incentives for utilities to make such investments are limited because of potential lost revenues from reduced demand as well as the potential for eventual competitive entry facilitated by automation of metering and billing functions.

Real time metering capability is necessary to allow for hourly monitoring and billing of power consumption. Without such capability, it is not possible to allocate the costs/benefits of demand response directly to consumers. Two-way communications systems for sending price or other control signals to consumers and receiving near real time load information to assess charges are necessary. The ubiquity of internet communications and the relatively small bandwidth required significantly reduce the costs of implementing such communications systems. Programs in Florida Power and Puget Energy that utilize real time metering along with programmable thermostats currently charge less than $5 per customer per month for participants in their demand response programs [4]. Economies of scope may allow such costs to be reduced significantly.

Utilities must significantly upgrade their billing systems to enable near real time charges and to manage the much larger degree of information flows. The information will also enable utilities to have a much greater knowledge of system conditions and should improve their ability to forecast load.

Information programs are necessary in order to educate consumers on the potential benefits and methodologies of demand response programs, including but not limited to – thermal storage, hourly pricing, metering and control equipment. Studies have shown that such programs can be effective at inducing consumers to change their consumption behavior even without price signals. [14,15,16,17,18]

Large scale demand response can be implemented with either distributed or a coordinated control. Distributed demand response allows consumers to make their own consumption/response decisions based on incentives provided by the utility/Load Serving Entity/system operator. These incentives can include pricing schemes such as real time pricing, time of use pricing, critical peak pricing, or demand bidding. Consumers receive a price signal and respond accordingly. Studies of pricing programs have found limited response (typically with elasticities on the order of –0.1 [16]). The majority of these studies, however, did not provide enabling technologies to the customers. Programs that do provide enabling technologies have found significant potential, however most of these programs fall under the coordinated type of DR below. [4]

Utilities or system operators coordinate several current demand response programs. In these programs, customers agree to reduce load at the direction of the utility. The contract will often include a limit to the number of hours the utility may declare a demand reduction event, and allow the demand to ignore the event at the cost of paying a penalty. Such programs enable the utility to predict the demand response and to attempt to coordinate the DR with the system conditions. The limitations include a limited number of hours, the lack of incentives for DR in non-event hours, and the lack of investment in true peak shifting equipment since most participants simply shut down all or part of their load in response to an event.

IV. System Wide Effects of Demand Response

This section examines the effects of large scale implementation of the thermal storage scheme outlined above. The individual case assumes that prices are unchanged by the actions of a single household. This assumption will hold in general, but when a sufficient number of consumers are participating in thermal storage market prices will be affected. A non-linear dynamic simulation model was used to evaluate the long run effects on market prices, generation capacity, and consumer savings from widespread adoption of thermal storage technologies.

The model uses data from the PJM system for the year 2003. The average air conditioning consumption in PJM is 640 KWh/yr [2]. The model uses a simple generation investment heuristic based on segment revenues to determine the effects of large-scale implementation of demand response on generation capacity. Consumers adopt the thermal storage according to their potential savings and awareness of the technology (via wor dof mouth). In addition, the model includes long term demand elasticity to include the rebound effect in the analysis.

The model segments the electricity market into base-load (18% of hours), intermediate (68% of hours), peak (13% of hours), and critical peak segments (1% of hours). Results from the optimization model outlined above were used as inputs to determine the amount of load shifted by each consumer from peak and critical peak hours to intermediate hours. A piecewise linear supply curve (See Figure 4) is used to determine the market clearing price; each segment is represented by the supply function. This curve was derived from the aggregate load and price data from PJM.

Figure 4 also shows the long term effects on the aggregate supply curve of implementing large scale demand response. The supply curve becomes steeper as peak load generation capacity is reduced due to a reduction in peak load. This mitigates the long term price savings seen by customers who do not participate (free riders) in demand response. On the other hand, the expected diminishing returns as more and more consumers participate, while still a factor, are also mitigated somewhat. It must be noted that even though the curve is steeper, the peak prices, on average, will be reduced significantly (nearly 25%) except for in the few critical peak hours when demand is highest.

Figure 4. Supply Curve with and without Load Shifting

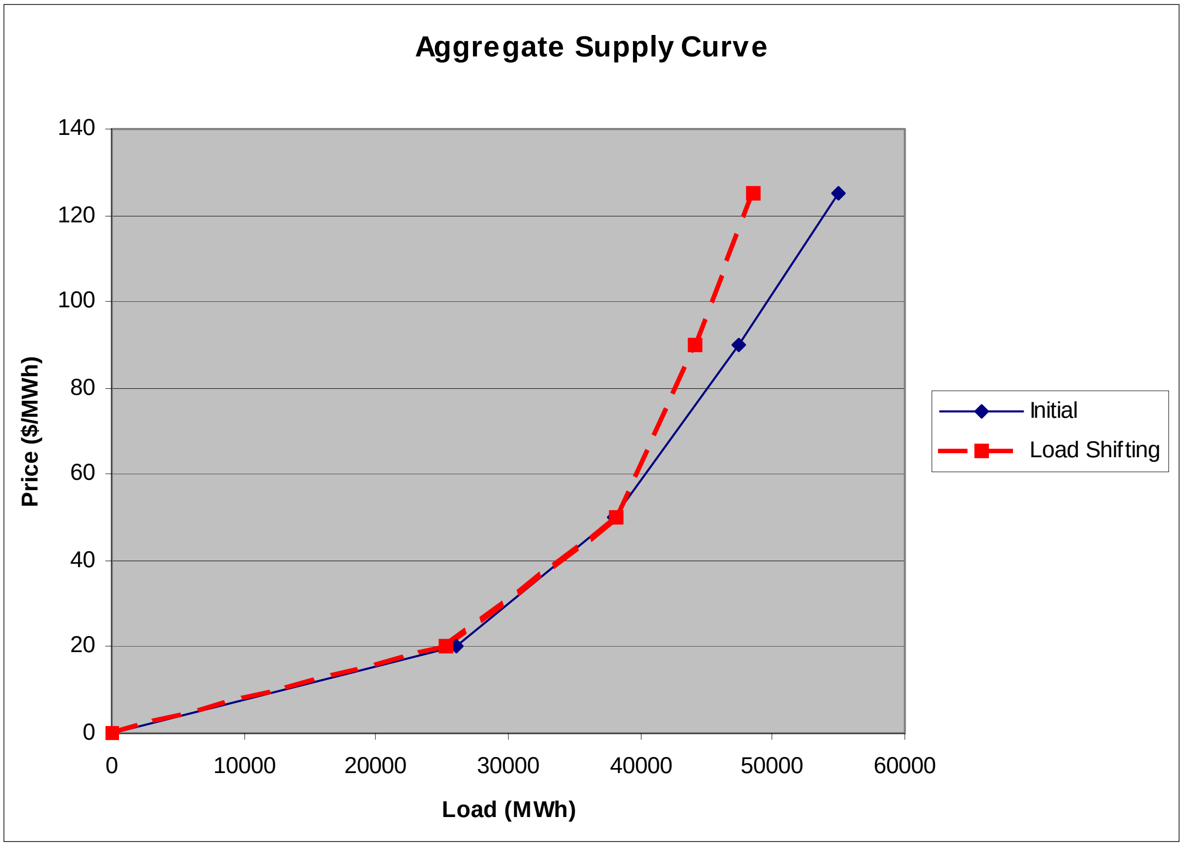


Figure 5. Generation Capacity by Sector

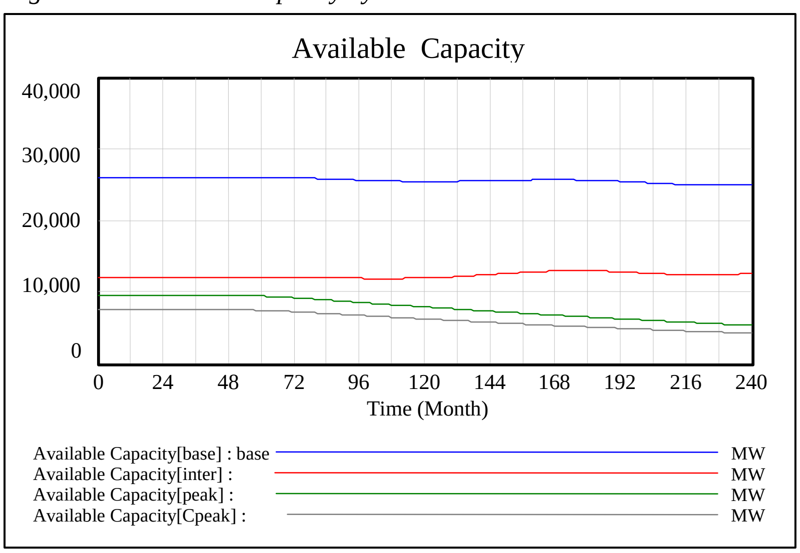
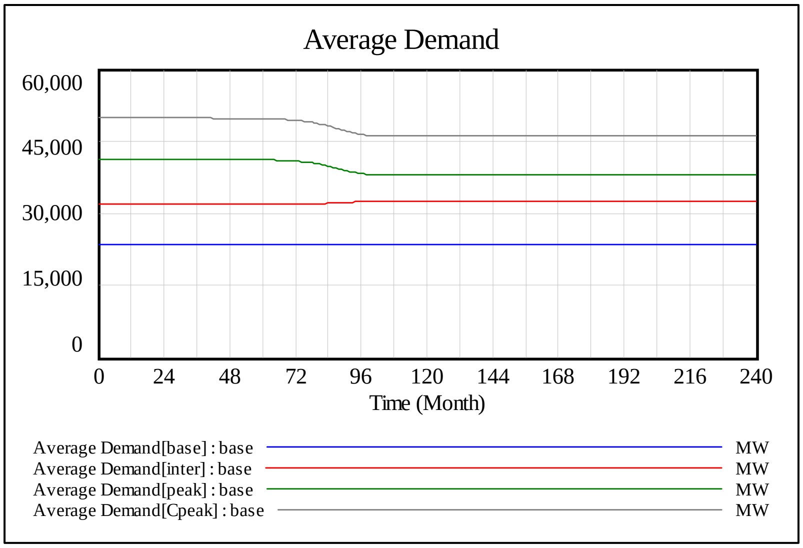


Figure 6. Average Hourly Demand by Segment



The results of the model indicate that demand in peak and critical peak hours is reduced by 8% (see Figure 6). System generation capacity is reduced by 12%. Base generation capacity decreases by 2%, intermediate capacity increases by 7% and peak capacity is reduced by 29%. Intermediate capacity increases due to a combination of higher utilization and increased prices in intermediate hours.

Because of diminishing returns, it is only cost effective for 25% of users to participate in load shifting. At this point, the costs of investing in the control equipment exceed the benefits of load shifting.

The model shows that the savings resulting from thermal storage are sufficient (in the PJM system) to cover the individual costs of installation, but not the system costs. Since all consumers benefit from the demand response program, it is not unreasonable to socialize the system costs. In addition, the externalities may prove large enough to justify some subsidization of the individual costs. Non-participants will receive the benefits of reduced costs and may otherwise free ride on the investments of participants.

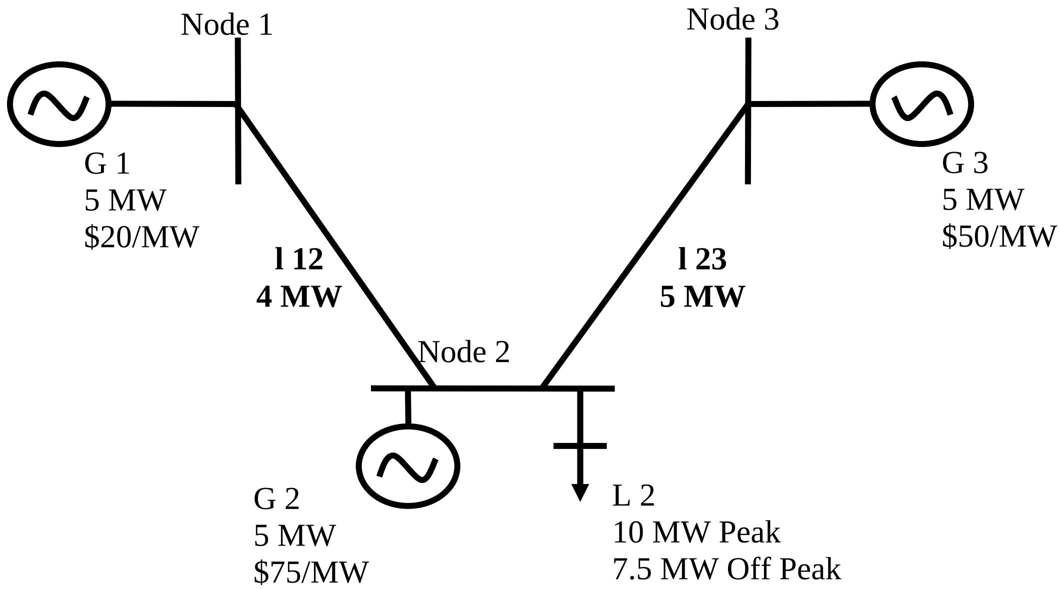
V. Investment Substitution with Demand Response

Reducing the peak load will directly impact the required transmission capacity since the system is built for the peak. The overall utilization of lines will also increase as the peak is reduced and the load smoothed. This will increase flow-based revenues for transmission companies, but will also reduce congestion charges.

Demand response also has significant potential to reduce the need for ancillary services. By smoothing the overall system load and shifting reactive power demand away from system peak loading, thermal storage will reduce the need for ancillary services such as VAR compensation, frequency control, and reserves. In addition to reducing the need for ancillary services from load shifting, demand resources can be utilized directly for VAR compensation, frequency control, and short term reserves.

As with traditional demand side management programs, investments in the infrastructure for demand response should include analysis of the avoided costs (least cost planning). The difference is that often investments in demand response infrastructure, such as real time metering, are an indirect method of reducing demand and therefore may be difficult to quantify. The infrastructure enables demand response and is a necessary but not sufficient component of demand response. The components of consideration should include reductions in spot prices (including LMP), the elimination of capacity expansion in generation, transmission, and distribution, and reductions in reserves and ancillary services. The value of demand response for increasing reliability is significant and should be included as well.

Figure 7. Example 3 node system



In the following example, the simple three-node system above is used to illustrate the potential avoided costs of transmission or generation expansion from DR.

In this system, the peak price will be $75/MW with 4MW from G1, 5 MW from G3, and 1 MW from G2. The off peak price will be $50/MW with 4MW from G1 and 3.5 MW from G3.

With 10% DR (assuming .5MW shifted before and .5 MW shifted after the peak time period) the load will be 9 MW peak and 8 MW off peak. Under these conditions, the price will be $50/MW in both peak and off peak hours.

For N-1 security criteria to be satisfied, the system would have to add 1 MW of capacity either to line 1-2 or to generator 2 without demand response. Demand response allows the N-1 criteria to be satisfied with no additional investments. This illustrates the value of demand response for improving system reliability. Demand response can also be used in contingency/emergency situations to shed load without major service disruptions, which would be a significant improvement over rolling blackouts.

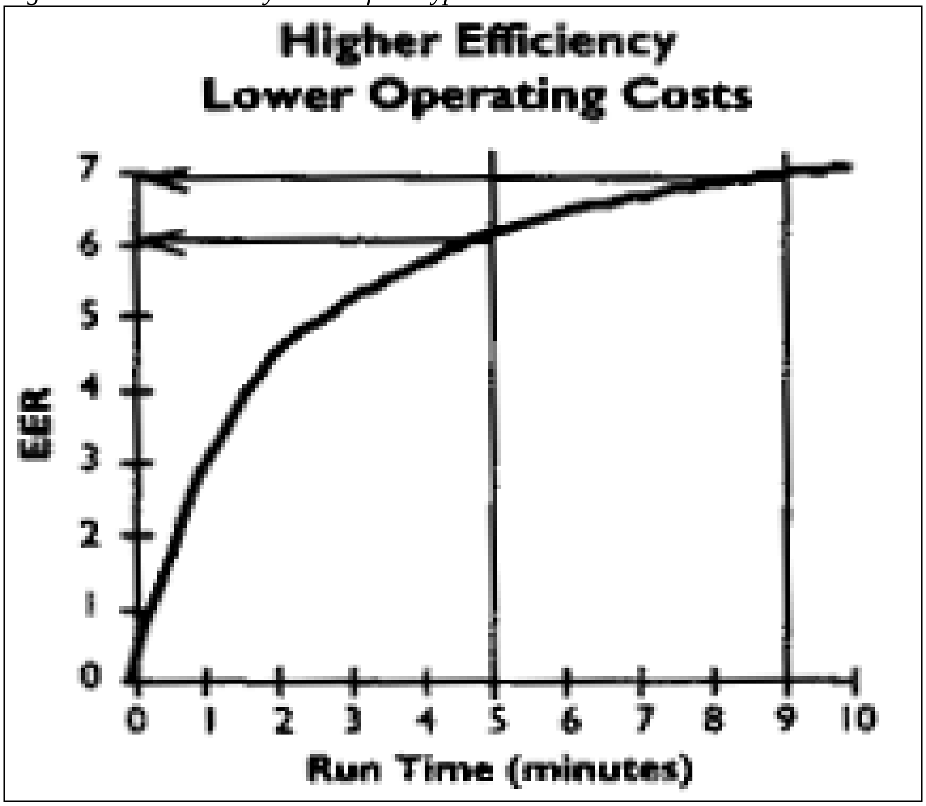
This example demonstrates the ability for demand response to substitute for capacity investments. The concept of avoided costs and least cost planning has been used for demand side management programs for many years. Typically the analysis of demand response programs includes only the direct economic savings from reductions in peak consumption. The indirect savings resulting from investments in infrastructure to support demand response, including reliability improvements and capacity substitution, should be incorporated in analysis of such investments.

VI. Additional Potential Benefits

There are multiple secondary benefits associated with technologies required for implementing demand response. These include improved efficiency of consumption, better customer service, and the potential for additional services.

The thermal control scheme will increase the cycle time of the air conditioner, which will also increase the efficiency and result in improved humidity reduction. The Energy Efficiency Ratio, EER (Btu/Wh) for air conditioners increases with cycle time, as does the amount of moisture that condenses and is collected. [12] (See Figure 8).

Figure 8. EER versus Cycle time for a typical Air Conditioner



It is likely that consumers with intelligent thermostats will reduce their consumption even more than the simple load shifting scenario outlined above. With greater control over temperatures and easier programming methods, consumers will be much more likely to allow their air conditioners to idle while they are away from home, thus possibly saving a great deal of electricity.

The automated metering systems also enable faster, more accurate fault detection since utilities can isolate the locations of faults as soon as they occur. They also increase customer service by providing more accurate billing and real time updates on changes to load. Additional services enabled by the metering and communications infrastructure include home security services and the bundling of water and natural gas metering.

Typical demand resopnse evaluations focus primarily on the avoided costs from reductions of peak prices. Additional savings are available from alleviating transmission congestion and eliminating the necessity of additional investments. Large Scale Demand response utilizing thermal storage has the potential to significantly increase efficiency of the electric power system and reduce the overall infrastructure capacity.

VII. Future Research

There are several areas of future research necessary to determine the long-term implications of large-scale adoption of demand response technologies. Research is necessary in engineering, economics, and political/social science. This research can be conducted through a combination of laboratory simulation and monitoring of ongoing implementations by innovative utilities.

In engineering, possible transient stability issues resulting from simultaneous action by loads in response to discontinuous pricing periods (currently hourly) should be investigated. The magnitude of complementary benefits such as increased efficiency from extending cycle times can also be determined. In addition, development of control algorithms that are cost effective, easily implemented, acceptable and understandable for residential consumers is a precursor for large-scale adoption. Methods to integrate demand response for ancillary services including frequency control, VAR support, and reserves also need

further development. [6,11] Protection schemes that integrate demand response have significant potential and should be pursued as well. Line losses will be reduced in the short term as demand response reduces loading, but may increase in the long term if overall utilization is increased due to higher load factors.
.
Open research issues in economics include: Determination of the costs of information and education programs to promote consumer acceptance of demand response technologies; Further studies of the potential savings to include reductions in market power and the real options value of response technologies; determination of the magnitude of rebound effects from reduced prices and whether such effects are more or less peak coincident than current demand profiles; Determination of the long term effects on investment in generation, transmission, and distribution, including the possibility of stranded assets; Evaluation of market clearing mechanisms and the potential for instability or oscillatory behavior due to lumpy response behavior; Evaluation of various market designs to determine the incentives for investments in demand response .

Political and Social research on coalition formation, stakeholders and status quo bias, regulatory support/capture and uncertainty, and consumer behavior can determine the conditions and incentive structures necessary to promote large scale implementation/adoption of demand response technologies.

Demand response technologies have the potential to dramatically change the operation of the electric power system and to increase the efficiency of capital investments. Further research can help determine stable pathways to integrate demand response into the current system architecture.

References

1. Constantopoulos, P., Schweppe, F. and Larson, R., "ESTIA: A Real-time Consumer control Scheme for Space Conditioning Usage Under Spot Electricity Pricing." C*omputers Operations Research*, vol 19, no. 8, pp 751-765, 1991.United States Department of Energy, *Residential Energy Consumption Survey (RECS)*, 2001. http://www.eia.doe.gov/emeu/recs/contents.html
3. Ilic, M.; Black, J.W.; Watz, J.L , "Potential Benefits of Implementing Load Control", *Proceedings IEEE Power Engineering Society Winter Meeting*, 2002 , Vol. 1 , pp. 177 -182, New York, NY, January 2002
4. United States Government Accountability Office, "Consumers Could Benefit from Demand-Response Programs, but Challenges Remain," August, 2004. http://www.gao.gov/new.items/d04844.pdf
5. *2001 ASHRAE Handbook: Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, GA, 2001.Black, J and Ilic, M., "Demand-Based Frequency Control for Distributed Generation", *Proceedings IEEE Power Engineering Society Summer Meeting*, 2002, Chicago, IL, July 2002.Black, Jason W., Ilic, Marija, "Survey Of Technologies And Cost Estimates For Residential Electricity Services", *Proceedings of the IEEE Power Engineering Society Summer Meeting*, July 2001."Review of Current Souther California Edison Load Management Programs and Proposal for a New Market-Driven, Mass-Market, Demand-Response Program", California Energy Commission, Feb 2004.Fumagalli, E.; Black, J.W.; Ilic, M.; Vogelsang, I., "Quality of Service Provision in Electric Power Distribution Systems Through Reliability Insurance", *IEEE Transactions on Power Systems*, Accepted for Publication, March 2004.Daryanian, B. "Scheduling of Electricity Consumption under Spot Prices." Ph.D. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1989.Ilic M., Skantze P., Yu C.N., Fink L., Cardell J., "Power Exchange for frequency control (PXFC)", *Proceedings of the IEEE PES Winter Meeting*, New York, NY, January 1999.Proctor, J., Katsnelson, Z., and Wilson, B, "Bigger is Not Better: Sizing Air Conditioners Properly", *Home Energy Magazine Online*, May/June 1995 .Isamu Matsukawa, **"**The Effects of Information on Residential Demand for Electricity," *The Energy Journal*, Vol.25, Iss. 1; pg. 1, 17 pgs, 2004.
14. Bushnell, J. and Mansur, E., "The Impact of Retail Rate Deregulation on Electricity Consumption in San Diego", POWER Working Paper (PWP-082), April 2001.
15. Caves, D. and Christensen, L, "Residential Substitution of Off-Peak for Peak Electricity Usage under Time-of-Use Electricity Pricing", *The Energy Journal*, Vol. 1, No. 2, 1980.

16. Caves, D., Christensen, L., and Herriges, J., "Consistency of Residential Customer Response in Time-of-Use Electricity Pricing Experiments", *Journal of Econometrics*, vol. 26, pp 179-203, 1984, North-Holland.Caves, D., Eakin, K., and Faruqui, A., "Mitigating Price Spikes in Wholesale Markets through Market-Based Pricing in Retail Markets", *The Electricity Journal*, April 2000.Braithwait, S. and Faruqui, A., "The Choice Not to Buy: Energy Savings and Policy Alternatives for Demand Response", *Public Utilities Fortnightly*, March 15, 2001.

Jason W. Black is pursuing a Ph.D. in Engineering Systems at MIT, focusing on electric power systems and regulation. He received a B.S. degree in Electrical Engineering and a B.A. in International Studies from the University of Notre Dame in 1994. He is a member of IEEE, IAEE. He is currently an NSF IGERT fellow, and previous honors include a Martin Fellowship for Sustainability and membership in Tau Beta Pi and Eta Kappa Nu. Mr. Black also has significant experience with the US Army and in Management Consulting. He can be reached at jwblack@mit.edu.