Energy Efficiency, Information Technology, and the Electricity System

Authors: Carl Blumstein
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Carl Blumstein
California Institute for Energy and Environment
University of California
2087 Addison Street
Berkeley, California 94704
USA
Email: Carl.Blumstein@uc-ciee.org

Abstract

Information technology can increase energy efficiency by improving the control of energy using devices and systems. Awareness of this potential is not new—ideas for applications of information technology for energy efficiency have been promoted for more than 20 years. But much of the potential gain from the application of information technology has not yet been realized. Explanations for the slow penetration of information technology solutions include the heterogeneity of energy users and uses, regulatory constraints, limitations of the technology, and market structure. In spite of these difficulties, there is reason for optimism going forward. This is because of a convergence of new requirements for operation of the electricity system—especially the need to make use of renewable generation that depends on resources, like the wind and the sun, that are beyond the control of system operators—and improvements in technology—especially reductions in the costs of information technology. This creates the possibility that the old paradigm for system operation in which supply is continuously adjusted to meet demand will be replaced by a new paradigm in which supply and demand are adjusted together to optimize system performance. Implicit in this new paradigm is better control of end uses of energy, which seems certain to reduce energy consumption. In this paper I examine the evolution of the new paradigm, identifying reasons for the slow pace of adoption and obstacles that must still be overcome. And I explain why adoption of the new paradigm is likely to lead to significant energy savings and other environmental benefits.

Introduction

Much of the way we live has been transformed by information technology. Revolutions ignited in North Africa, small children mesmerized by games on smart phones . . . But the transformative effects of information technology are not much in evidence in our electricity systems. Information technology is, of course, widely used in the electricity industry—accounting, record keeping, high speed communications, and similar applications are integral parts of modern businesses. But the potential—recognized toward the end of the last century—to change the way electricity systems operate has yet to be realized.

This paper examines both barriers to change and the potential benefits that change could bring to the electricity industry. Among the barriers considered are the inertia created by regulatory systems, difficulties in accommodating the heterogeneity of both usage and users of electricity, costs (especially on the residential scale), and the structure of the markets for providing electricity and for providing control technology to end users of electricity.

Overcoming these barriers will have a significant payoff in two areas, more efficient use of energy and optimization of electricity system performance. Information technology can provide the ability to better adjust demand in response to supply conditions. This creates the possibility that the old paradigm for system operation in which supply is continuously adjusted to meet demand will be replaced by a new paradigm in which supply and demand are adjusted together to optimize system performance.

Efficiency gains come from better control of end uses. Significant improvements in control can result from manual actions that are enabled by better monitoring. This might involve actions like repairing equipment that is found to be broken or getting janitorial staff to turn off lights when they leave. Automatic control can turn things off when they are not needed (for example, by turning off electric lighting when sensors detect that the lighted area is unoccupied) and can adjust equipment to meet the needs of the moment (for example, reducing electric lighting when daylight is available). More sophisticated control systems can also take control actions in anticipation of future conditions (for example, in response to weather forecasts).

The paper concludes with a discussion of strategies that can be employed to overcome the barriers and speed the pace of innovation. Most importantly, we need to learn from the Internet—the strategies that have made the Internet so open to innovation can be adapted for applications of information technology to the electricity system.

Barriers

In an optimistic paper presented almost twenty years ago Blumstein, Rosenfeld, and Akbari (1993) wrote, "Within the next few decades the transmission and distribution networks that deliver electric power to our homes and factories will be paralleled by communications networks and electric meters will be replaced by computers. This new information technology will transform the industry in three ways: (1) existing operations will become more automated, (2) the generation, transmission, and distribution plant will be used more efficiently, and (3) a range of additional services will be offered."

Blumstein *et al*. were not the only optimists and the optimism has not been limited to applications of information technology to the electricity system. Laitner (2002) and Romm (2002) both suggested that the transformative impacts of information technology could improve energy productivity in many areas of the economy. As examples Romm points to possible energy savings from improved inventory management, reduced need for retail floor space because of Internet shopping, and reduced need for commuting and commercial office space because of telecommuting. More recently, Laitner and Ehrhardt-Martinez (2008) argue that information technology has in fact caused and will continue to cause energy efficiency gains in many areas.

Although we are still a long way from achieving the changes in the electricity system envisaged by the optimists, optimism about the transformative potential of information technology persists (see, for example, Fox-Penner, 2010). These expectations have been accompanied by substantial investments by the federal government in information technology under the American Recovery and Reinvestment Act (Executive Office of the President, 2010). Much of the recent investment has gone toward funding Advanced Metering Infrastructure (AMI). AMI provides a gateway that could enable real-time pricing, but, thus far, very little has passed through the gate.

Given the speed with which other applications of information technology are developing, how can we account for the lack of progress on applications to energy? And what should we think about current predictions for the transformative effects of information technology?

Heterogeneity

Information technology is not a device like a water heater, or a furnace, or any of the many other kinds of equipment that deliver energy services. Rather, it provides a mechanism for improving the quality of energy services by controlling devices. There are many different uses and users of electricity that can benefit from improved control. These uses and users are not only very heterogeneous, they are constantly changing. This heterogeneity and dynamism is a challenge—there are no one-size-fits-all solutions. What is needed is an information technology infrastructure that can accommodate diversity and adaptation.

Regulation

During California's electricity crisis of 2000-2001, a strong case was made for real-time pricing (RTP) and the Legislature appropriated ~$30 million to enable RTP by installing non-communicating interval meters that could record consumption of electricity in 15-minute intervals for all customers whose demand exceeded 200kW. A decade after the meters were installed the regulator has just begun to implement a variant of RTP called critical-peak pricing. A decade is several product cycles in the world of information technology. This example illustrates the profound inertia typical in the US regulatory system. Changes have both winners and losers and regulators are very averse to creating losers. Much of the delay in implementing the new pricing was the result of potential losers opposing changes in adversary proceedings and regulators struggling to minimize the number of losers and the size of any losses.

Market structure

Key players shaping the role of information technology in the electricity system are the utility companies and controls companies. Each of these institutions has limitations that have slowed the pace of innovation in the electricity system.

In the US, the utility industry is fairly fragmented—there are more than one hundred utilities of significant size and several thousand utilities in total. The companies typically spend very little on R&D and have few specialists in information technology on staff and almost never in senior management. The culture is focused on service and reliability—not innovation.

Companies that provide control systems for heating, ventilation, air conditioning (HVAC), and other building services are important mostly in larger facilities. Controls companies have an interesting similarity to utilities—service is a key part of their business models. And the success of their service business depends in part on customer "lock in." That is, it is very much in the interest of the controls companies to make it difficult for its customers to switch suppliers.

A central reason that it is difficult to switch control system suppliers is embedded in the system architecture used by the controls companies. In the language of information technology, the systems installed by controls companies typically use "vertical architecture." A more flexible architecture, "horizontal architecture," makes it easier to work with multiple suppliers. Horizontal architecture promotes competition and innovation. There is more about this later in the paper. Here I note that the distinction between vertical and horizontal controls architecture is not well understood by many of the people engaged in the promotion of energy efficiency in buildings. Building technologists and information technologists do not speak the same language (indeed, the word "architecture" has quite different meanings for the two professions). This language barrier is, in itself, a significant impediment to progress.

Possibilities

Electricity system optimization

Proponents of energy efficiency have often ignored larger questions of system optimization. In part this is because demand response[1] has sometimes been framed as an alternative to energy efficiency. Some demand response strategies can actually increase energy consumption because, although they decrease on-peak consumption, they increase off-peak consumption more than they decrease on-peak consumption. But ignoring system optimization is short sighted for at least three reasons: (1) in many cases demand response decreases on-peak consumption more than it increases off-peak consumption (see discussion in Goldman *et al.*, 2010 pp 2.1-2.14), (2) the information technology needed for demand response is, for the most part, also the information technology needed for energy efficiency, and (3) demand response has an important role to play in the integration of renewable energy into the electric grid.

One of the drivers for increased use of information technology on the grid has been the desire to implement time-varying prices. With the advent of increased competition in wholesale electricity markets it became obvious to many observers and some regulators that economic efficiency gains would result from better connection between retail and wholesale prices. California provided a striking example of problems that can result when wholesale prices are completely disconnected from retail prices (Blumstein, Friedman, and Green, 2002).

While time-varying pricing should lead to improved system efficiency, information technology may also enable more profound efficiency gains. These gains involve a shift in the system operation paradigm. In the old paradigm electricity supply is adjusted to meet demand. In the new paradigm supply and demand are adjusted together to optimize system performance. Proving out the new paradigm opens the door for much more effective integration of new supplies like renewables and new loads like electric vehicles (Callaway and Hiskins, 2011). And it opens the door for an information technology infrastructure that will greatly improve energy management in buildings.

Exploiting storage opportunities

It is widely known that energy storage can help the management of peak loads and the integration renewable supplies that fluctuate with wind speed or solar irradiation. It is less well known that a substantial amount of relatively low-cost energy storage is available in the thermal inertia of buildings and devices like refrigerators. Building temperature is typically controlled within some range. For example, the range might be between 23.5°C and 25.5°C when cooling is required. If, when supply is adequate, buildings are cooled to the lower end of the temperature range, then, when supplies are tight, cooling can be stopped until the temperature reaches the top of the range. The length of the resultant reduction in demand will depend on the thermal mass of the building and the thermal loads on the building and can range from a few minutes to more than an hour. If many buildings are available and if supply is not too constrained, then, with proper control and coordination, it will be possible to use the thermal inertia of the buildings to ride through a period of tight supply with little or no impact on the comfort of building occupants.

[1] Sometimes called load management, demand response strategies attempt to make energy use more responsive to system operating requirements and costs.

Curtailing demand

When supply is not adequate to meet demand it is necessary to reduce demand in order to prevent system collapse. This can be accomplished by simply shutting down sections of the electricity grid but it has long been recognized that it is more efficient to drop selected loads rather than shutting down whole sections of the grid. Some tools for doing this have long been available. For example, since the 1980's California utilities have had programs for residential consumers that have enabled the utilities to turn off participants' air conditioners in response to supply constraints. These programs use a broadcast signal for one-way communication between the utility and the participants. One disadvantage of this strategy is that utilities do not know which air conditioners are best positioned for interruption and participants do not have the ability to override utility instructions. Better systems for communicating utility instructions to large non-residential customers are becoming available (Kiliccote *et al*., 2010), but coordination among customers, which requires two-way communication, is rare.

Storage strategies that use thermal inertia are a subset of curtailment strategies—the overall objective of these strategies is to reduce demand in periods of constrained supply by interrupting the consumption that is least valuable. Often storage best meets this objective because it does not result in any diminution of occupant comfort.

Energy efficiency and information technology

The first payoff from the deployment of information technology is often the result of better monitoring of energy usage. For most electricity users the quantity of energy they are using is opaque. Typically, they only receive a report about their electricity consumption once per month and often they have little idea about how their actions might affect their electricity consumption. Good monitoring can enable consumers to see the effects of their actions in near-real time. In a review of studies of the effect of the feedback of consumption information to residential consumers Ehrhardt-Martinez,, Donnelly, and Laitner (2010) find that the closer the information is to real time the greater its effect on consumption. When near-real time information includes appliance-level detail, the reduction in consumption can be about 10 percent.

In larger buildings good monitoring enables building operators to identify previously unrecognized dysfunction and energy waste. For example, enabled by good monitoring, manual, human-based diagnostic techniques have identified problems with chiller cycling, air in chilled water pipes, fan power oscillations, improperly functioning controls, and other malfunctions (Piette, Khalsa, and Haves, 2000). These findings have led to the establishment of monitoring-based commissioning (MBCx) programs. MBCx systematically encourages building operators to use monitoring to continuously evaluate building performance so that operations and maintenance problems can be identified and corrected. Results from an MBCx program on university campuses suggest that MBCx programs can be very cost effective (Brown and Anderson, 2006).

The first payoff from automatic control of energy usually comes from turning things off when they are not needed—in short, doing nothing well.[2] This strategy has been pursued for many years using devices that manage on-off schedules. Examples are time clocks that turn off HVAC equipment during the night in buildings that are not used at night and programmable thermostats that adjust temperature settings according to schedules set to accommodate occupant preferences. But these elementary controls are often unreliable. Programmable thermostats are notoriously difficult to program and surveys suggest that, more often than not, they are not programmed correctly (Meier, et al. 2010).

The application of information technology can improve the performance of these types of controls in several ways. As noted above, good monitoring can help building operators know if controls are working properly. More importantly, the control devices can be improved by adding better programming and communications capabilities. An example of this is the programmable communicating thermostat (PCT). A low-cost version of this device has been developed (Do *et al*., 2007) and is now available commercially. PCTs can communicate by wireless to home computers so that programming can be done with full-screen graphical user interfaces instead of small liquid crystal displays, making the job easier for many people. The PCT's ability to communicate also enables it to coordinate with the grid—during hot days the PCT can be instructed to set the temperature up a few degrees thus reducing demand when capacity is short.

Reductions in the costs of sensors and actuators and wireless communications are making it feasible to introduce new controls, such as systems that reduce lighting in unoccupied spaces, in existing buildings. More sophisticated control systems can learn time constants for building warm up and cool down from experience and can use these constants together with weather forecasts to optimize building start times. Such systems can also more effectively manage processes like night-time ventilation for cooling (see Dounis and Caraiscos, 2009 for a review of advanced controls). The possibilities for innovation are great, especially if interoperability increases (see discussion below).

[2] This slogan was proposed by Professor David Culler at the University of California, Berkeley.

Lessons from the Internet

One vision of how the technology for home energy management and grid coordination should evolve is the creation of specialized networks. An example of this in the residential sector is the ZigBee Alliance (www.zigbee.org). The alternative is to make use of the Wi-Fi networks that now exist in many US homes. Five years ago proponents of specialized networks argued that Wi-Fi was not sufficiently secure, that the cost of Wi-Fi was too high, and that the power consumption of Wi-Fi chips was too great. Part of the argument for specialized networks was that home energy management should be offered as a universal service. Because all consumers do not have access to broadband, it would be incumbent on the utilities to provide the necessary communications infrastructure. At least some of the specialized networks would not be redundant with Wi-Fi networks and so the potentially lower cost of specialized networks was important.

Now it seems harder to justify specialized networks. In addition to avoiding the cost of a redundant network, proponents of the Wi-Fi approach point out that Wi-Fi chips are continuing to get cheaper and low power Wi-Fi chips are becoming available. Perfectly secure wireless is not available, but there are many security applications for Wi-Fi—very secure Wi-Fi is available. Security applications are not yet available for specialized networks and the resources available to develop security applications are tiny compared to the resources available for supporting security applications for Wi-Fi. Finally, broadband access is increasing and the subscriber base is growing. For example, in California 96% of household have broadband access and 62% are subscribers (Public Policy Institute of California, 2009).

Equity concerns may still need to be addressed, but it seems better to subsidize access to broadband than to subsidize the deployment of specialized networks. California is now actively addressing the inequities that arise from the "digital divide" (see www.cetfund.org).

Probably the most important lesson from the Internet is interoperability—the ability of the Internet to accommodate diverse devices and systems and enable them to work together. The practical effect of interoperability is that equipment suppliers and software developers can compete to supply established needs and can innovate to create new uses. This environment has fostered both cost reductions and rapid innovation. So, one may well ask, can we make building monitoring and control systems look like the Internet? The answer is, yes we can.

Doing this is facilitated by using Internet architecture and Internet protocols. The most important step is to move from vertical architecture to horizontal architecture. Figure 1 provides a simplified representation of layered architecture[3] to help explain the concept. The bottom layer in Figure 1, here called the sensor/actuator layer, is where the monitoring and control system interacts with the building environment, gathering data and implementing control actions. The narrow waist organizes, stores, and transmits data from the sensor/actuator layer and instructions from the supervisory layer. The top layer, known as the supervisory layer, has software applications that operate on data provided through the narrow waist to provide outputs in the form of information on the state of the building and instructions for the control of building systems. Not all control is initiated on the supervisory layer; some happens autonomously on the sensor/actuator layer—for example, lights might be directly controlled by an occupancy sensor. And not all instructions from the supervisory layer are accepted. For example, a smoke alarm may override an instruction to open a damper. Within the layers a variety of languages (protocols) may be used for communication, but between layers a single language (protocol) is used for communication—the narrow waist only speaks Internet protocol (IP). To make this more concrete, consider a building appropriately equipped with sensors, actuators, and applications. Suppose that the operator of the building wishes to minimize energy use during the peak time on a hot day by precooling the building so it can ride through the peak time. An application in the supervisory layer contains a model of the building that can predict the best time to turn on the chillers based on the outdoor temperature, the indoor temperature, the wind speed, the weather forecast, and other variables all of which are resident in a data base in the narrow waist. The application gets the data from the data base and predicts the best time to turn on the chillers, say, 7:00AM. If sensors and controllers in the sensor/actuator layer determine that operation is safe, the chillers will be turned on at 7:00AM.

The difference between horizontal and vertical architecture is not in the functions that need to be performed. Sensing and actuating, data management and applications need to happen in monitoring and control systems regardless of the architecture. The difference is in the separation of these functions. In a vertical system a "black box" might, for example, have hard-wired connections to sensors and actuators and have applications with built-in data structures that were inaccessible to other applications. Horizontal layered architecture keeps the functions from becoming entangled and allows devices and software from different suppliers to inter-operate.

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[3] The phrase "layered architecture" does not refer to spatial relationships among the system's components; rather, it refers to logical relationships. The "layers" are an abstraction. Here I am using the word layers as a heuristic; it has more specialized meanings in other contexts.

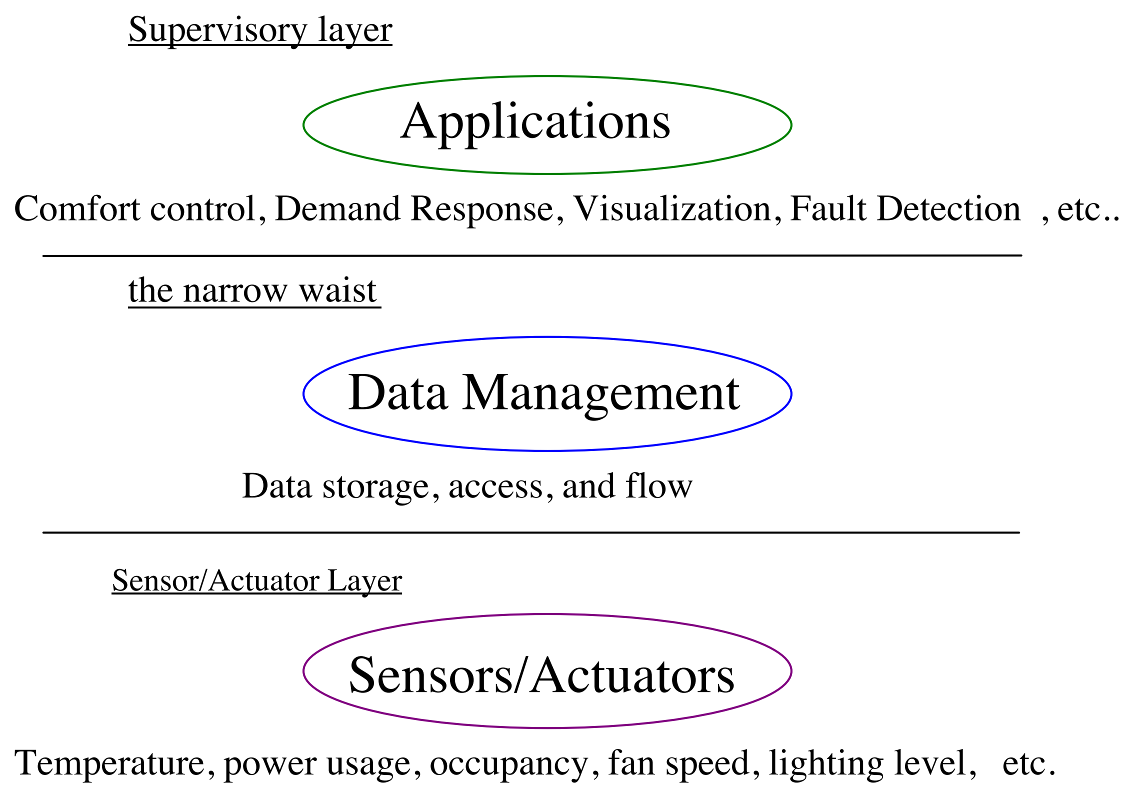

Figure1. A simplified representation of layered architecture for building monitoring and control

Conclusions

Given the current landscape for the application of information technology to the management of energy use, there are, in my view, some first steps that should be taken to speed the pace of innovation. First on the agenda is regulation. Regulators need to make it clear that energy management systems will not be provided as a universal service. As noted above, the heterogeneity of users and uses means that one-size-fits-all solutions are not practical and attempts to implement such solutions will almost certainly slow the process of innovation. In particular, regulators should act to create an environment in which a variety of energy management strategies can be implemented on existing Wi-Fi-based home networks.

California provides an instructive example of the problems that can be encountered on the way to creating an open environment for home energy management technologies. Utilities in California are well along in a program to install electronic meters for their residential customers. These meters include a low-power radio that can communicate the amount of power flowing through the meter in near-real time. However, these radios are not turned on and the utilities are unwilling to turn them on, even for experimental purposes. According to the utilities, the low-power radios they have installed are incapable of secure communication. The business reasons for the utilities' position are not clear. One possibility is that the utilities are concerned that they could be liable for damages that might result from the interception of communications between the meter and the household. A less generous explanation is that the utilities may want to develop a communications package for the low-power radios that will favour specialized networks that the utilities can control. Whatever the case, it seems reasonable that the householder should have the option of having her low-power radio turned on. The regulator should require that, to exercise the option, she must waive the right to damages if communications from the radio are intercepted. More importantly, the regulators must make it clear that energy-management technology inside the home will not be subject to monopoly control.

The path to an interoperable energy-management environment in larger facilities is not as clear as it is for residences. As discussed earlier in the paper, the technology of the Internet provides a recipe for interoperability. The key is to move from vertical to horizontal system architecture. However, the necessary systems are expensive and the risk of parting from established controls companies is not likely to be undertaken without subsidy. This area seems ripe for publicly-funded demonstration projects, which done at sufficient scale can discover and resolve technical problems and reduce the risk for private parties. The advantages of interoperability are sufficiently great that, once initial resistance is overcome and the technology is available from one or more suppliers, established controls companies will probably have to change their offerings.

Changing the paradigm for electricity system operation is more challenging still. Moving from a system in which supply is adjusted in response to demand to a system in which supply and demand are adjusted together to optimize system performance requires a convergence of programs for demand response and the technology for the control of end uses. Current demand response programs are focussed on "events," that is, episodes when supply is very constrained because of extreme weather or equipment failure. With rare exceptions, current control technology is isolated from the operation of the grid. Convergence requires that demand response programs change from an orientation toward responding to events to an orientation toward continuous response to the state of the system and that control technologies change from local isolation to strong connection to the system. A key driver for this convergence is the need to integrate electricity from renewable resources into the system. A key first step in moving toward a new paradigm for system operation is the creation of a regulatory framework that will foster the needed convergence.

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References

Blumstein, C., A. H. Rosenfeld, and H. Akbari, 1993, "Utility and Customer Communication, Computing, and Control (UC-3C) Technologies," in Oren, S. S., and S. A. Smith, eds., *Service Opportunities for Electric Utilities: Creating Differentiated Products*, Kluwer, Boston. http://uc-ciee.org/downloads/Blumstein%20et%20al%20UC_3C-1.pdf (accessed 24/02/2001)

Blumstein, C., L. S. Friedman, R. J. Green, 2002, "The History of Electricity Restructuring in California," *Journal of Industry, Competition and Trade,* 2(1), 9.

Brown, K. and M. Anderson. 2006. "Monitoring-Based Commissioning: Early Results for a Portfolio of University Campus Projects." Proceedings of the 13th National Conference on Building Commissioning, Portland, OR.: PECI. (http://www.peci.org/ncbc/proceedings/2006/05_Brown_NCBC2006.pdf) (accessed 10/03/2011)

Callaway, D.S. and I. A. Hiskens, 2011, "Achieving Controllability of Electric Loads," *Proceedings of the IEEE* 99-1, pp. 184-199.

Do, Alexander, David M. Auslander, William J. Burke, Richard M. White, and Paul K. Wright, 2007, *Technical Review of Residential Programmable Communicating Thermostat Implementation for Title 24-2008*, California Institute for Energy and Environent, Berkeley, CA http://uc-ciee.org/downloads/PCT_Draft_Final_Report.pdf (accessed 16/03/2011)

Dounis, A.I. and C. Caraiscos, 2009, "Advanced control systems engineering for energy and comfort management in a building environment—A review," *Renewable and Sustainable Energy Reviews*, 13, pp. 1246–1261

Ehrhardt-Martinez, Karen, Kat A. Donnelly, and J. A. Laitner, 2010, *Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities*, Washington, D.C.: American Council for an Energy-Efficient Economy.

Executive Office of the President, 2010, *The Recovery Act: Transforming The American Economy Through Innovation* pp. 37-41, The White House, Washington, DC. http://www.whitehouse.gov/sites/default/files/microsites/Recovery_Act.PDF (accessed 20/02/2011)

Fox-Penner, Peter S., 2010, *Smart Power: Climate Change, the Smart Grid, and the Future of Electric Utilities*, Island Press, Washington, DC.

Goldman, Charles, Michael Reid, Roger Levy and Alison Silverstein, 2010**,** *Coordination of Energy Efficiency and Demand Response*, Lawrence Berkeley National Laboratory, Berkeley, CA http://eetd.lbl.gov/ea/ems/reports/lbnl-3044e.pdf (accessed 18/03/2011)

Kiliccote, S., M.A. Piette, J. Mathieu, K. Parrish, 2010, **"**Findings from Seven Years of Field Performance Data for Automated Demand Response in Commercial Buildings," *Proceedings of the 2010 ACEEE Summer Study on Energy Efficiency in Buildings*, Washington, D.C.: American Council for an Energy-Efficient Economy. http://drrc.lbl.gov/pubs/lbnl-3643e.pdf (accessed 24/02/2011)

Laitner, J. A., 2002, "Information Technology and U.S. Energy Consumption: Energy Hog, Productivity Tool, or Both?" *Journal of Industrial Ecology*, 6-2, pp. 13-24.

Laitner, J.A. "Skip" and Karen Ehrhardt-Martinez, 2008, *Information and Communication Technologies: The Power of Productivity; How ICT Sectors Are Transforming the Economy While Driving Gains in Energy Productivity*, Washington, D.C.: American Council for an Energy-Efficient Economy.

Meier, Alan, Cecilia Aragon, Therese Peffer and Marco Pritoni, 2010, *Thermostat Interface and Usability: A Survey*, Lawrence Berkeley National Laboratory, Berkeley. http://escholarship.org/uc/item/59j3s1gk (accessed 20/02/2011)

Piette, M.A., S.T. Khalsa, and P. Haves, 2000, "Use of an Information Monitoring and Diagnostic System to Improve Building Operations." *Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings*. 7:101-112. Washington, D.C.: American Council for an Energy-Efficient Economy.

Public Policy Institute of California, 2009, *Californians and Information Technology,* PPIC, San Francisco. http://www.ppic.org/content/pubs/survey/S_609MBS.pdf (accessed 19/02/2011)

Romm, Joseph, 2002, "The Internet and the new energy economy," *Resources, Conservation and Recycling*, 36 pp. 197-210