Look Back before Leaping Forward: Four Decades of Domestic-Energy Inquiry

Reducing domestic energy consumption has a long, varied history, embracing pervasive computing, technology, sociology, and economics. The authors provide an overview and key references to help readers explore this rich background more deeply and broadly.

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Sustainability and stimulating pro-environmental behavior are increasingly popular themes at major conferences and satellite workshops, attracting many thought-provoking submissions on energy-related topics (for example, the Workshop on Ubiquitous Sustainability at UbiComp 2007 and the Pervasive Persuasive Technology and Environmental Sustainability Workshop at Pervasive 2008). Although "green" issues and sustainability have prompted much recent activity, domestic-energy-consumption research has a history that some will find surprisingly long and diverse, spanning multiple fields including psychology and economics.

Here we provide a brief overview of research in this space, including historical and more current work, across many disciplines. Although we focus on domestic energy consumption, much of this survey applies to broader research, including personal consumption outside the home as well as workplace and public energy use. We cover only a fraction of the prior research even in domestic energy, focusing on references we hope will be good starting points for understanding the field's long, many-threaded history. We encourage energy-consumption researchers to both inform themselves of past research and consider cross-disciplinary approaches to maximize their impact.

Nothing New under the Sun

Domestic-energy-use research began in the 1970s in parts of Europe and the US. A desire for energy independence, highlighted by the oil crises in late 1973 and mid-1979, largely motivated this research. Oil prices fell in the 1980s, but an increased focus on urban smog and acid rain raised awareness of energy use's impacts. In the 1990s, global warming received public attention, and since the turn of the century, it's been considered part of the more general issue of *sustainable development*—the idea that we should treat resources such that later generations will be able to meet their needs. So, whereas the emphasis has shifted owing to the different motivations for reducing domestic energy use, efforts to understand and mitigate this problem have existed for nearly 40 years.

Over this time, many articles like this one have encouraged a research community to examine a potentially forgotten past. As early as 1981, Gordon McDougall and his colleagues categorized more than 600 publications dealing with what they characterized as "consumer energy research," classifying 76 of these as "overview/discussion papers."[1] Their summary focused on consumer studies and covered an array of topics including basic opinion survey results,

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energy consumption modeling, and intervention techniques such as feedback and incentives.

In 1992, Paul Stern wrote an article for the psychology community that summarized energy conservation results from the 1970s and early 1980s.[2] According to Stern, whereas environmental policy and research funding waned in the 1980s, energy and environmental concerns regained public attention in the early 1990s. Stern specifically urged psychology researchers to avoid past mistakes and instead build on those early results, stay practical, and use language sympathetic to policymakers. (For more information on psychology literature related to feedback, see "The Design of Eco-Feedback Technology."[3])

Two years later, Joel Scheraga was explicit about the problem's age—this section's heading is a line from his text.[4] Scheraga wrote for the economics community, highlighting the difficulty of predicting the effects of technological innovation and incentives, and modeling energy producers' and consumers' behavior.

A Many-Sided Problem

Past research has addressed domestic energy consumption using four broad approaches:

- providing feedback to expose energy-consumption details to users;
- using technology-driven interventions to sense and control energy use;
- implementing economics-based strategies, such as incentives, to reduce energy demand; and
- examining social factors concerning energy-use practices.

Each has its own history and take on the overall problem.

Feedback

A recurring strand in energy efficiency research that's particularly popular now is providing people feedback on their energy consumption. This approach draws users further into the loop, letting them make more informed decisions about the energy they consume.

As many have argued, domestic energy consumption tends to be less tangible than other forms of consumption, such as driving an automobile or using a pay-as-you-go mobile telephone. Topping-off the tank or phone account requires active participation. But the sole indicator of home energy consumption is usually a monthly bill, and utility companies often will average out seasonal usage variation and charge equal amounts each month. Many researchers have tried to improve on this situation—for example, by increasing monthly bills' information quality or detail and providing stimuli, such as comparisons with historical or normative usages, to reduce consumption.[5,6]

The earliest feedback studies were in the mid-1970s and ranged from feedback on monthly bills,[7] to daily handwritten feedback on a 3 × 5 in index card placed in each household's mailbox,[8] to real-time feedback on an in-home monitoring device.[9] These consumer studies tended to run for months and involved hundreds or thousands of homes.

Whereas the research literature indicates that feedback, even as simple as daily notes pushed under the door, can have a positive effect—typically yielding 5 to 20 percent savings[10]—these effects are often short lived. And some studies, such as one in 1977 by Richard Katzev and his colleagues, found no statistically significant difference between four test groups both with and without feedback, and with and without an award if a participant reduced consumption.[11] As Stern observes, it isn't simply the information but its credibility, ability to capture attention, and usefulness in a given situation that aid in motivation.[2] Setting predefined conservation goals can lead to more powerful or longer-lasting effects, as L.T. McCalley and Cees Midden explored using salient appliance-integrated feedback.[12] However, presenting normative comparisons requires care so that those with below-average consumption don't increase their use in response to such feedback (the "rebound effect").[13]

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Researchers have also explored the effects of finer-grained feedback, rather than bulk feedback on the entire home. Tsuyoshi Ueno and his colleagues studied nine highly instrumented homes in Japan, providing each household with an information display on which participants could view the daily or 10-day load curves for domestic appliances and heating and ventilation systems.[14] The system showed cost in 30-minute intervals, with options to compare these to the previous month or the same month in the previous year. During the two months following installation, the power consumption for eight households decreased an average of 9 percent. Power consumption for heating systems decreased by 23 percent. Significantly, per-appliance feedback had a discernible impact: TV power use decreased by 5 percent, and users adjusted refrigerators to save power and unplugged devices to reduce standby consumption. Consumption for devices on the display fell by 12 percent on average, whereas consumption for devices that weren't included fell by 5 percent.

The pervasive computing community has lent its expertise to the area of feedback and its effects—from core sensing technologies to interaction design.[3] The effectiveness of energy-consumption-display (ECD) designs has been less comprehensively explored. Georgina Wood and Marcus Newborough provide several thought-provoking observations on ECDs and posit a framework for choosing whether to display feedback local to a device or via a central household display depending on a simple taxonomy of user interaction with appliances.[15] They comment on the importance of credible, fine-grained information as well as the effectiveness of self-comparison, rather than comparison to others.

Technology-Centric Solutions

Another research area relevant to pervasive computing is technology-centric solutions—for example, sensing and control systems that mediate energy use, thereby reducing consumption. In this article, we've largely assumed active user involvement, but opportunities certainly exist to create smarter, more adaptive infrastructures, buildings, and appliances that work in harmony with occupants as well as energy providers to find new ways to reduce consumption and carbon externality.

Motivated by the needs to better meet and manage consumer energy demand and to more easily leverage renewables and microgeneration, developers have shifted their focus to the smart grid—integrating digital communications, power delivery, and smarter metering. Twenty-eight US utilities are committed to rolling out smart meters to their customers in the next few years, and the UK promises coverage of all households (47 million meters in 26 million properties) by 2020. Even simple smart meters offering automated meter reading can enable finer-grained pricing designed to encourage off-peak use and, of course, more user accountability. Recent large-scale smart-meter pilot deployments in more than 800 households illustrate financial savings in 90 percent of households, with energy-use reductions of up to 25 percent in the summer using peak-rate pricing (www.powercentsdc.org). Advanced metering infrastructures (AMIs) that integrate metering, control, and feedback throughout the home permit two-way communication between energy providers and household appliances. To flatten spikes in demand, AMIs can trigger certain appliances at off-peak times or when surplus energy is available—a process called *demand-response management*.

In the past five years, displays have gained popularity and are available off-the-shelf in some countries. An impressive array of products offers consumers low-cost energy monitoring and feedback. Energy Inc.'s Energy Detective, OWL's Wireless Electricity Monitor, Blue Line Innovations' PowerCost Monitor, Wireless Monitors Australia's Cent-a-Meter, and DIY Kyoto's Wattson all provide wireless displays using a transmitter that augments the household electricity meter or main electricity feed. Variants of these types of meters, such as Current Cost and the Efergy E2 wireless monitor, are useful for designing custom interventions, offering RS232 or USB connectivity to stream data to a computer. RFXCOM (www.rfxcom.com) manufactures a 433.92-MHz receiver with a USB, LAN, or WLAN interface that can intercept data from some of the sender units and many popular home automation protocols.

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Per-appliance monitoring is possible with off-the-shelf products. Users can connect Kill-A-Watt (www.p3international.com) inline with appliances to measure their energy use and that use's associated cost. Several off-the-shelf commodity wireless sensor networks are specifically for in-home energy monitoring. Plogg (www.plogginternational.com), Plugwise (www.plugwise.com), and AlertMe (www.alertme.com) all offer ZigBee (IEEE 802.15.4) wireless-mesh-based smart plug units used inline with appliances. These devices typically measure with a cumulative accuracy of ±5 percent (+0.5 watts/–2.5 watts) at EU voltages (230 volts AC, 50 Hz) and can sense loads of 1.5 to 16 amperes for appliances up to 3.68 kilowatts.[16] Onboard batteries and memory allow these devices to survive power outages, and let users turn off the data-gathering PC. The nodes themselves have minimal energy impact, nominally using less than 10 watts.

Increasingly, systems such as AlertMe are sold in place of smart meters and allow similar reporting of energy use to Web-based portals, such as Google PowerMeter (www.google.com/powermeter) and Microsoft Hohm (www.microsoft-hohm.com). These portals offer historical and normative usage comparisons.

Plogg provides a software development kit and binary protocol specification for third-party developers. The home-automation community has partially reverse-engineered the Plugwise protocol, letting developers write plug-ins for home-automation toolkits.[17] AlertMe is a closed system with a low-cost subscription, but it can export data to Google PowerMeter. Google has recently announced an API offering programmatic data access.[18]

Research prototypes. Recently, researchers have used sensor networks to accomplish fine-grained appliance-level sensing and control. Xiaofan Jiang and his colleagues' ACme consists of a wireless Epic (open mote platform) module with an energy-metering integrated circuit to provide real, reactive, and apparent power measurements, with optional attached appliance control.[19]

ACme hardware schematics and software are both open source.

Younghun Kim and his colleagues' ViridiScope—currently using Crossbow MicaZ wireless sensor nodes running TinyOS, HMC1002 magnetic sensors, and MTS310 sensor boards—follows a different path.[20] It uses indirect sensing, rather than conventional inline (effectively in-circuit) sensing, and estimates power consumption by observing second-order effects of appliance use, such as magnetic fields and light. This intriguing approach is less cumbersome and easier to deploy but requires dense deployments, is potentially less accurate, and doesn't offer actuation.

Algorithms. As Jiang and his colleagues pointed out, modern electronic devices comprise many subcomponents and have distinguished power traces per state that uniquely identify them.[19] Analyzing power-line transients and their power signatures to identify appliances in use isn't a new concept. George Hart and his colleagues invented the nonintrusive appliance load monitor (NALM) at MIT in the early 1980s and later provided a reference summary.[21]

A traditional NALM uses a single digital AC monitor attached to the domestic power supply. An edge detector picks up voltage and current changes, which are then clustered on a 2D space of real versus reactive power. NALM pairs positive and negative clusters of similar magnitude (different appliances being turned on and off) and can distinguish two appliances with the same total power by differences in their complex impedance. This approach is sensitive enough to differentiate devices with the same nominal rating, such as light bulbs, owing to their natural variation. It models appliances with multiple components as state machines rather than base components (motors, heaters, and so forth). The ease with which such systems can be deployed—especially inside smart meters or by outside agents such as utility companies—and the detailed information they yield naturally raise privacy concerns.

Hart's steady-state approach is highly effective in homes and small businesses with few concurrent events and low electrical noise. Christopher Laughman and his colleagues later extended NALMs to deal with more complex electrical environments.[22] These systems use higher harmonics in the aggregate current signal to distinguish loads with overlapping clusters, and the load transients' distinctive shape helps them recognize individual loads. Shwetak Patel and his colleagues showed how to use machine-learning techniques to classify electrical events in the home from electrical noise (transients) with a success rate of 85 to 90 percent.[23]

Heating and ventilation have a major energy impact in the home. Understanding a building's thermal performance is important for anticipating energy use and calibrating for seasonal effects, such as outdoor temperature. Rather than modeling a given building's detailed structure and thermal properties, Robert Sonderegger proposed and experimentally validated an elegant approach based on six equivalent thermal parameters: thermal mass; solar window area; furnace field effect; and three transfer constants between indoors, a temperature clamp, and the house structure.[24] The approach enabled accurate hour-by-hour internal temperature estimates in different weather situations.

Practical lessons from home automation. Newborough and Douglas Probert postulated how you might target major electrical appliances to help regulate peak power demand, highlighting opportunities for smarter control and automation.[25] They flagged challenges for a lower-energy future including low rates of replacement of major appliances; few financial incentives for manufacturers to produce lower-energy-consuming appliances; and sociological notions of comfort, affluence, and expectation of always available energy.

Newborough and Probert found opportunities for unobtrusive load management across appliances, including shedding loads on a hierarchical basis. For example, freezers' compressors can switch off for up to 30 minutes without apparent inconvenience. With well-insulated storage, water can heat up during off-peak periods—rather than on demand—without compromising the consumer experience. Appliances with regular demand curves can shift to off-peak times. Certain appliances can power off (rather than remain on standby) when rooms are empty for a certain period. Automated systems can flag abnormal or excessive loads. This approach is similar to Michael Mozer's Neural-Network House,[26] which aimed to automatically program the house to optimize its systems for its occupants, although environmental impact wasn't the principal driver.

Regarding automating domestic systems, we must mention the dedication and achievements of hobbyist home automators, who have been monitoring and reducing home energy consumption since the 1980s. A range of standards, products, and ad hoc solutions now address domestic and commercial building and appliance automators' needs and are extremely useful for ubicomp technology developers. For a sophisticated example of home automation and real-time online reporting, visit www.bwired.nl. For portals for the home automation community, see www.automatedhome.co.uk and www.homeautomation.com.

Economics and the Energy Gap

Economics researchers have examined energy consumption in terms of both optimizing pricing to individuals and industry and finding solutions outside direct pricing. The goal is to help public policy and regulation create energy markets that function beneficially for society in the long term.

Since the late 1970s, economists have been investigating why rational economic models often fail to predict how individuals and large organizations will respond to economic incentives to reduce consumption.[27] The mismatch between rational economic efficiency and real behavior became known as the *energy gap*. Adam Jaffe and Robert Stavins posited that the energy gap is due to two types of failures. *Market failures*, such as a lack of information about efficient appliances or when the principal user isn't paying for the energy directly, keep actors from making optimal decisions. *Nonmarket failures* include uncertainty about future energy prices, as well as qualitative attributes (for example, individuals preferring incandescent lighting to fluorescent).[28] In the 1990s, some economists described types of failures using "barrier models," which explained why certain actors make irrational decisions regarding energy consumption in specific cases.[29]

Researchers are also concerned that energy consumption's impact isn't accounted for in its cost. In other words, the cost to the purchaser or user is much lower than the actual cost to society. Of course, assessing the total societal cost is prohibitively difficult—it requires reliable estimates of elements including existing energy reserves and future environmental conditions, such as climate change. An alternative approach compares current energy consumption to the energy likely to be available in the long term. David MacKay provided a highly accessible introduction offering a "balance sheet" between reasonable expectations for consumption and possibilities for sustainable production.[30]

Many nations supply information to potential purchasers about their decisions' implications. Examples of this strategy include prominently displayed ratings for domestic appliances and public bodies that provide advice to people renovating or upgrading their home building or infrastructure. However, even when accurate information is available, people will often choose less-efficient investments. Such behaviors fall in the category of nonmarket failures; economists have called them *behavioral failures*. Behavioral failures include biases toward the status quo ("thermal solar heating isn't very popular, so it's probably not worth it") and the salience effect of immediate or easily observable costs ("solar heating panels are so expensive that I can't possibly save money in the long run").[31] Behavioral failures in economics are founded on strong observations about individuals' behavior from fields such as psychology and sociology, but verifying them empirically at large scales is difficult.

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Social Practices

Significant sociological research has observed and analyzed people's routine practices (such as cooking, bathing, and cleaning) and how such practices arose. Sociologists have taken this rich data and used it as a lens to understand how these practices affect energy consumption. Factors other than financial economy and personal preference—including technology affordances, the built environment and infrastructure, and sociocultural norms—heavily influence personal and domestic consumption.[32]

In the context of both individual behavior and sociotechnical approaches, Tracey Crosbie provided a review of home energy consumption.[33] As she pointed out, of the more than 30 years of quantitative research, most studies focus on behavior modeling, with a small amount of more recent sociotechnical qualitative studies. Crosbie called for an integration of these historically distinct types of inquiry. Studies will be most powerful when the longitudinal and detailed measurements associated with consumer and behavior work are combined with the nuanced and detailed sociological and ethnographic accounts of people's everyday practices. Similarly, Charlie Wilson and Hadi Dowlatabadi called for a reconciliation of individual behavior-based models and sociotechnical ones.[34]

Studying and modeling human behavior can inform design,[3] but casting consumption as an individual behavior tends to imply that people make completely sovereign choices, which discounts the effect of social expectations. For example, persuasive technologies that aim to change behavior might have minimal impact when the practices they try to influence are heavily determined not by information availability or individual preferences but by norms concerning proper care of the family, the presumed social expectations of guests in the home, or deeply ingrained definitions of healthy living and comfort.

Pervasive technology designers and practitioners play a crucial role in validating, refining, and re-creating consumption norms. This is especially true in the home, where practices wrapped up in comfort and cleanliness determine much of consumption. Elizabeth Shove outlined and critiqued these practices in "Changing Human Behaviour and Lifestyle: A Challenge for Sustainable Consumption?"[35]—an essential read for anyone working on domestic consumption.

A Riddle, Wrapped in a Mystery, inside an Enigma

Despite intensive efforts across a variety of fields over several decades, the problem of reducing domestic energy consumption is by no means solved. One reason is a lack of matching public resources and policy to implement findings. (Dramatic changes to personal consumption tend to be unpopular.) Again, the motivations for understanding consumption have changed over the years, and the framing and focus of inquiry have evolved. So, both our motivations for solving the problem and our understanding of its causes are constantly shifting.

Another reason solutions elude us is that the studies' results can be highly context dependent. As we mentioned, findings on domestic consumption depend heavily on socioeconomic factors, the country of residence, and culture. However, consumption is even less generalizable than that: findings aren't necessarily transferable to the next appliance, the next month, or next door.

Domestic energy consumption is often cast as an issue new technologies should address.[33] With purely technological approaches, the focus is on optimizing efficiency, which obscures the core issue—reducing consumption. An example close to home is the wording used in the call for papers for this *IEEE Pervasive Computing* special issue on smart energy systems. The call refers repeatedly to the problem of energy management and implies that favorable solutions are ones automated through technology and that the future of energy is minimally invasive, optimal, and dynamically adaptive. Similarly, in earlier sections of this article, we used phrases such as "smarter control" and "without compromising the consumer experience." Such an exclusively technological framing can marginalize alternative yet synergistic approaches.

Deep lifestyle changes will be required over the next few generations. One alternative to a fundamental shift in practices is to support the increasingly universalized standards for indoor environments (for example, between 20° and 22° C). However, many people would argue that such standards are unsustainable, especially at a global scale.[35] New technologies should complement these behavior changes, for instance, through better energy-consumption apportionment to individual actions or habits. If people don't embrace the evolution of practices now, even more dramatic consumption changes will be necessary in the future. As Garrett Hardin argued 42 years ago, in any situation in which many people share limited resources, increased coercion—regulatory or economic—will likely be required to avoid catastrophe.[36]

Starting more than 15 years ago, numerous calls have been made for multidisciplinary approaches to domestic energy. This is where the pervasive computing community can truly shine. Rather than approaching the problem from any one discipline, researchers should carefully consider alternative data collection and analysis methodologies and theoretical framings of energy consumption.

In addition to any initial approaches—ethnography, sociotechnical studies, sensing technology, algorithms, interaction design, or application deployment—a wide variety of background reading is absolutely critical. We hope that the references we've given make this easier. Have a look at a few older references, or ones from fields of study with which you might be less familiar. What you find might surprise you.

Before doing any domestic deployments, involve those with other approaches—theoretical and methodological—to participate in your study's design and implementation. As Crosbie observed, qualitative and quantitative data can be used to corroborate, interpret, and unpack one another, and careful analysis of both together is crucial for new understandings of domestic energy.[33]

REFERENCES

1. G.H.G. McDougall et al., "Consumer Energy Research: A Review," *J. Consumer Research*, vol. 8, no. 3, 1981, pp. 343–354.
2. P.C. Stern, "What Psychology Knows about Energy Conservation," *Am. Psychologist*, vol. 47, no. 10, 1992, pp. 1224–1232.
3. J. Froehlich, L. Findlater, and J. Landay, "The Design of Eco-feedback Technology," *Proc. 28th ACM Conf. Human Factors in Computing Systems* (CHI 2010), ACM Press, 2010, pp. 1999–2008.
4. J.D. Scheraga, "Energy and the Environment: Something New under the Sun?" *Energy Policy*, vol. 22, no. 10, 1994, pp. 798–803.
5. S. Darby, "Making It Obvious: Designing Feedback into Energy Consumption," *Proc. 2nd Int'l Conf. Energy Efficiency in Household Appliances and Lighting*, Springer, 2000, pp. 685–696.
6. A. Faruqui, S. Sergici, and A. Sharif, "The Impact of Informational Feedback on Energy Consumption—a Survey of the Experimental Evidence," *Energy*, vol. 35, no. 4, 2010, pp. 1598–1608.
7. C.S. Craig and J.M. McCann, "Assessing Communication Effects on Energy Conservation," *J. Consumer Research*, vol. 5, no. 2, 1978, pp. 82–88.
8. R.G. Bittle, R. Valesano, and G. Thaler, "The Effects of Daily Cost Feedback on Residential Electricity Consumption," *J. Behavior Modification*, vol. 3, no. 2, 1979, pp. 187–202.
9. L. McClelland and S. Cook, "Energy Conservation Effects of Continuous In-Home Feedback in All-Electric Homes," *J. Environmental Systems*, vol. 9, no. 2, 1979, pp. 169–173.
10. B. Farhar and C. Fitzpatrick, *Effects of Feedback on Residential Electricity Consumption: A Literature Review*, tech. report SERI/TR-254-3386, Solar Energy Research Inst., 1989.
11. R. Katzev, L. Cooper, and P. Fisher, "The Effect of Feedback and Social Reinforcement on Residential Electricity Consumption," *J. Environmental Systems*, vol. 10, no. 3, 1981, pp. 215–227.
12. L.T. McCalley and C. Midden, "Making Energy Feedback Work," *User Behavior and Technology Development*, P.-P. Verbeek and A. Slob, eds., Springer, 2006, pp. 127–137.
13. P.H.G. Berkhout, J.C. Muskens, and J.W. Velthuijsen, "Defining the Rebound Effect," *Energy Policy*, vol. 28, nos. 6–7, 2000, pp. 425–432.
14. T. Ueno et al., "Effectiveness of an Energy-Consumption Information Sys-

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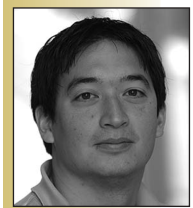

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tem on Energy Savings in Residential Houses Based on Monitored Data," *Applied Energy*, vol. 83, no. 2, 2006, pp. 166–183.

15. G. Wood and M. Newborough, "Energy-Use Information Transfer for Intelligent Homes: Enabling Energy Conservation with Central and Local Displays," *Energy and Buildings*, vol. 39, no. 4, 2007, pp. 495–503.
16. *Getting Started with Plugwise: Installation Manual*, Plugwise, 2010; www.plugwise.com/sites/default/files/manuals/2010-07-21_Installation%20manual%20Home%20Start,%20Home%20Basic/installation_manual_en_20100630_web.pdf.
17. "Plugwise Protocol Unleashed Part 1: Introduction," blog, 24 Jan. 2010, www.maartendamen.com/?p=89.
18. "Google PowerMeter API Introduced for Device Manufacturers," blog, 3 Mar. 2010, http://blog.google.org/2010/03/google-powermeter-api-introduced-for.html.
19. X. Jiang et al., "Experiences with a High-Fidelity Wireless Building Energy Auditing Network," *Proc. 7th ACM Conf. Embedded Networked Sensor Systems* (SenSys 09), ACM Press, 2009, pp. 113–126.
20. Y. Kim et al., "Viridiscope: Design and Implementation of a Fine Grained Power Monitoring System for Homes," *Proc. 11th Int'l Conf. Ubiquitous Computing* (Ubicomp 09), ACM Press, pp. 245–254.
21. G. Hart, "Nonintrusive Appliance Load Monitoring," *Proc. IEEE*, vol. 80, no. 12, 1992, pp. 1870–1891.
22. C. Laughman et al., "Power Signature Analysis," *IEEE Power & Energy Magazine*, vol. 1, no. 2, 2003, pp. 56–63.
23. S. Patel et al., "At the Flick of a Switch: Detecting and Classifying Unique Electrical Events on the Residential Power Line," *Proc. 9th Int'l Conf. Ubiquitous Computing* (Ubicomp 07), ACM Press, 2007, pp. 271–288.
24. R. Sonderegger, "Diagnostic Tests Determining the Thermal Response of a House," *Trans. Am. Soc. of Heating Refrigerating and Air-Conditioning Engineers*, vol. 19, no. 12, 1977, pp. 35–47.
25. M. Newborough and S.D. Probert, "Intelligent Automatic Electrical-Load Management for Networks of Major Domestic Appliances," *Applied Energy*, vol. 37, no. 2, 1990, pp. 151–168.
26. M.C. Mozer, "The Neural Network House: An Environment that Adapts to Its Inhabitants," *Proc. Am. Assoc. Artificial Intelligence Spring Symp. Intelligent Environments*, AAAI Press, 1998, pp. 110–114.
27. M.L. Dennis et al., "Effective Dissemination of Energy-Related Information: Applying Social Psychology and Evaluation Research," *Am. Psychologist*, vol. 45, no. 10, 1990, pp. 1109–1117.
28. A.B. Jaffe and R.N. Stavins, "The Energy-Efficiency Gap: What Does It Mean?" *Energy Policy*, vol. 22, no. 10, 1994, pp. 804–810.
29. L. Weber, "Some Reflections on Barriers to the Efficient Use of Energy," *Energy Policy*, vol. 25, no. 10, 1997, pp. 833–835.
30. D.J.C. MacKay, Sustainable Energy—without the Hot Air, UIT, 2009.
31. K. Gillingham, R.G. Newell, and K. Palmer, "Energy Efficiency Economics and Policy," *Ann. Rev. Resource Economics*, vol. 1, no. 1, 2009, pp. 597–620.
32. H. Wilhite et al., "The Legacy of Twenty Years of Energy Demand Management: We Know More about Individual Behaviour but Next to Nothing about Demand," *Society, Behaviour, and Climate Change Mitigation*, Springer, 2000, pp. 109–126.
33. T. Crosbie, "Household Energy Studies: The Gap between Theory and Method," *Energy & Environment*, vol. 17, no. 5, 2006, pp. 735–753.
34. C. Wilson and H. Dowlatabadi, "Models of Decision Making and Residential Energy Use," *Ann. Rev. Environment and Resources*, Nov. 2007, pp. 169–203.
35. E. Shove, "Changing Human Behaviour and Lifestyle: A Challenge for Sustainable Consumption?" *The Ecological Economics of Consumption*, L.A. Reisch and I. Ræpke, eds., Edward Elgar Publishing, 2004, pp. 111–131.
36. G. Hardin, "The Tragedy of the Commons," *Science*, vol. 162, no. 3859, 1968, pp. 1243–1248.