Look Back Before Leaping Forward: Four Decades of Domestic Energy Enquiry

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ABSTRACT
The problem of reducing domestic energy consumption is a hot topic in the pervasive computing and CHI communities, though it is also one with a long and varied history. In this survey we give a brief overview of the history and current state of four approaches to this problem, from feedback-oriented and technology-centric systems found in pervasive computing, to social factors research and economics-based studies. We aim to provide an introductory set of references that allows readers to explore the rich background of this topic more deeply and broadly, and complement more focused reviews already published.

INTRODUCTION
The issue of sustainability and stimulating pro-environmental behaviour is increasingly a theme at major conferences and satellite workshops1, attracting a number of thought provoking submissions on energy related topics. While “green” issues and sustainability have motivated many recent efforts, research in domestic energy consumption has a history that some will find surprisingly long and diverse, spanning multiple fields such as psychology and economics. The purpose of this survey is to provide a brief overview of research in this space, including historical as well as more current work and spanning a number of disciplines. While we focus on domestic energy consumption, much of this survey is relevant to broader research, including personal consumption outside the home as well as workplace and public energy use. However, in this short article we can cover only a fraction of the prior work even within domestic energy; we focus on references which we hope can serve as good starting points for getting to grips with the long and many-threaded history of the field. We hope to encourage those doing research involving energy consumption both to inform themselves of past work, and to consider cross-disciplinary approaches to maximise their impact.

“Nothing new under the sun”
As part of the enquiry on consumption, research into domestic energy usage began in the 1970’s in parts of Europe and the United States. This was motivated largely by a desire for energy independence, highlighted by the oil crises in late 1973 and mid-1979. Oil prices fell again in the 1980’s, but increasing attention to urban smog and acid rain increased awareness of real impacts of energy usage. In the 1990’s, the concept of global warming was brought to the fore, and since the turn of the century this has been popularly 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. Thus, while the emphasis has been shifting between the different motivations for solving the problem, efforts at understanding and mitigating domestic energy usage have existed for nearly forty years.

Given this history, it may not be surprising that there have been a number of papers over the years which, like this paper, appeal to a research community to look to a potentially forgotten past. As early as 1981, McDougall et al. categorised over six hundred publications dealing with what they characterised as “consumer energy research”; seventy-six of these were classed as “overview/discussion papers” [20]. Their summary was written primarily for the field of consumer studies, and covered an array of topics, including basic opinion survey results, energy consumption modelling, and intervention techniques such as feedback and incentives.

In 1992, Paul Stern wrote an article for the psychology community [27], which summarised “energy conservation” results from the 1970’s and early 1980’s. According to Stern, while environmental policy and research funding had waned in the 1980’s, the early 1990’s were a time when energy and environmental concerns were regaining public attention. Stern specifically urged psychology researchers “to avoid past mistakes”, and encouraged them to instead to build on those early results, and to strive to stay practical and to use language sympathetic to policymakers.

Two years later, Joel Scheraga was even more explicit about the age of the problem [24]—it is a line from his text which

1In pervasive computing, examples of such events include Workshop on Ubiquitous Sustainability: Technologies for Green Values (UbiComp 2007); Pervasive Persuasive Technology and Environmental Sustainability (Pervasive 2008), Ubiquitous Sustainability: Citizen Science & Activism (UbiComp 2008); and Defining the Role of HCI in the Challenges of Sustainability (CHI 2009).

2For a dedicated treatment of psychology literature with regard to feedback, we refer the reader to Froehlich et al. [9].
appears in our heading above. Scheraga was writing for the economics community, and highlighted the difficulty of predicting the effect of technological innovation and incentives, and modelling energy producer and consumer behaviour.

A many-sided problem
In this survey, we focus on the problem of reducing domestic energy consumption and how this problem has been interpreted across four broad approaches: providing feedback to expose details of energy consumption to users, technology-driven interventions to sense and control energy use, economics-based viewpoints on how incentives can be used to reduce demand for energy, and social factors concerning energy use practices. Each has its own history and its own take on the overall problem, and we now discuss each in the order above.

FEEDBACK
A recurring strand in energy efficiency work, which has become particularly popular recently, has been on providing feedback to people on their energy consumption. This addresses the overall problem of reducing energy consumption by drawing the human further into the loop; enabling more informed usage decisions and therefore allowing users to reduce the overall energy they consume.

As many have argued and shown before, domestic energy consumption tends to be less tangible to people compared to other forms of consumption such as driving an automobile or using a pay-as-you-go mobile telephone—“tapping up” the tank or the phone account require active participation. By contrast, the often sole indicator of home energy consumption is the monthly bill, and even then seasonal variation in use are often averaged out by utility companies in favour of charging equal amounts from month to month. Many researchers have attempted to understand and improve upon this situation, by for example, experimenting with increasing the quality or detail of information provided on bills, and providing stimuli such as comparisons with historical or normative usages to trigger reduced consumption behaviours [5, 8].

The earliest studies of feedback were undertaken in the mid-1970’s, ranging from feedback on monthly bills [3]; to daily feedback handwritten on a 3×5 in index card, and put in the mailbox by mid-morning [2]; or, in fact, displayed in real time on an in-home monitoring device [19]. These feedback and intervention consumer studies tended to run for months, and involved hundreds or thousands of domiciles.

In the past five years, displays have been used more widely (and are available off-the-shelf in some countries) to provide direct real-time feedback. While the consensus in the literature seems to be that feedback (even as simple as daily notes pushed through the door) can have a positive effect, typically yielding 5%–20% savings [7], these effects are often short lived and there is controversy—some studies, such as one by Katzev et al. in 1977, found no statistically significant difference between four test groups (with/without feedback, with/without a ‘decal’ awarded if a reduction was achieved). As Stern observes: it is not simply the information given, but its credibility, ability to capture attention and usefulness in a given situation that aids motivational effect [27]. The setting of pre-agreed conservation goals can lead to more powerful or longer lasting effects as McCalley explored using salient appliance integrated feedback [18]. Care is certainly required when presenting normative comparisons, that those with below average consumption don’t in fact increase their use in response to such feedback (the ‘rebound effect’ [1]).

The effects of finer-grained, rather than whole home, feedback has also been explored. Ueno et al. studied 9 highly instrumented homes in Japan [28], providing each household with an information display from which participants were able to display the daily or 10 day load curves for domestic appliances, heating and ventilation systems. The system showed cost in Yen binned in 30 minute intervals, with options to compare these to the previous month or the same month a year previously. Over the two months following installation, an average reduction in power consumption of 9% was found for 8 of the households. Power consumption due to heating reduced by 23%. Significantly, per appliance feedback had a discernible impact: usage patterns changed with TV power usage down by 5%, refrigerators adjusted to save power, and devices unplugged to reduce overall standby consumption. Consumption for devices included on the display fell by on average 12%, whereas those that were not included fell by just 5%.

As an area where the pervasive computing community can lend expertise—from core sensing technologies to interaction design—feedback and its effects have garnered much attention recently [9]. The nature of what forms energy energy consumption display (ECDs) should take to maximise their effectiveness is a less comprehensively explored space. Wood and Newborough provide several thought provoking observations based on the literature and posit a framework for choosing whether to display feedback with a device or via a central household displays depending on a simple taxonomy of appliances [32]. They comment on the importance of credible, fine-grained information, and the effectiveness of self comparison (rather than comparison against for example neighbours).

TECHNOLOGY-CENTRIC SOLUTIONS
Another thrust of research of relevance to pervasive computing is in seeking technology-centric solutions, i.e. installing or augmenting sensing and control systems to mediate energy use and thereby reduce energy consumption. In the previous discussion we have largely assumed active user involvement. We would also acknowledge that there are certainly opportunities for creating smarter more adaptive infrastructures, buildings and appliances that work in harmony with occupants, and indeed energy providers, to find new ways to reduce consumption and reduce carbon externality. We briefly attempt to capture commodity and research systems that may serve as enablers for conducting research in this area.

Motivated by both the need to better meet and manage con-
suser demand for energy and to more easily exploit opport
unities to leverage renewables and micro-generation, there
is a shift toward the ‘smart grid’: integrating digital commu
nications, power delivery and smarter metering. 28 utilities
in US are committed to rolling out smart meters to their cu
stomers in the next few years, with coverage of all households
in UK (47 million meters in 26 million properties) promised
by 2020. Even simple smart meters offering automated me
ter reading can enable finer grained pricing designed to en
courage off peak use, and of course, more accountability
and feedback to users. Recent large scale smart meter pi
lots of 800+ households illustrate financial savings to 90%
of households with reductions in energy use of up to 25%
in the summer using peak rate pricing. Advanced metering in
frastructures (AMI) integrating metering, control and feed
back throughout the home permit two-way communication
between energy providers and household appliances; allow
ing certain appliances to be triggered when surplus energy
is available and at off peak times to flatten spikes in demand: a
process known as demand response management.

In the interim, there is an impressive array of commercial
products available aimed at offering low cost energy moni
toring and feedback to consumers. Energy, Inc.’s ‘The En
ergy Detective’, OWL Wireless Electricity Monitor, Blue
Line Innovations’ PowerCost Monitor, Wireless Monitors
Australia’s Cent-a-Meter, and DIY Kyoto’s Wattson display,
all offer wireless displays driven by a transmitter that aug
ments the household electricity meter or mains electricity
feed. More useful to designing custom interventions are
variants on these types of meter such as CurrentCost or Ef
ergy E2 Wireless Monitor that offer RS232 or USB connectivity
options to enable data to be streamed to a computer. RFX
COM manufacture a 433.92MHz receiver with USB, LAN
or WLAN interface that can intercept data from some of the
sender units and many popular home automation protocols.

Per-appliance monitoring is possible with off the shelf prod
ucts: Kill-A-Watt can be plugged inline with appliances to
allow its energy use and its associated cost to be measured.
There are several off the shelf commodity wireless sensor
networks designed specifically for in home energy moni
toring: Plogg, Plugwise and AlertMe all offer a ZigBee
(IEEE 802.15.4) wireless mesh based ‘smart plug’ units that
are again used inline with appliances (ZigBee nodes must be
within 10m of each other). These devices typically measure
with a cumulative accuracy of ±5% (+0.5W / -2.5W) at EU
voltages (230V AC, 50Hz) and are capable of sensing loads
of 1.5-16A for appliances up to 3.68KW. Onboard batter
ies and memory allow the devices to survive power outages
and for the data gathering PC to be powered off. The nodes
themselves have minimal energy impact, nominally using
less than 10W. Increasingly systems such as AlertMe are
sold in place of ‘Smart Meters’ and allow similar reporting
of energy use to Web based portals offering historical and
normative comparisons, such as Google PowerMeter and
Microsoft Hohm.

For third party developers, Plogg provides an SDK and bi
ary protocol specification. As they have done with many
other sensing and actuation technologies, the home automa
tion community have managed to partially reverse engi
neer the PlugWise protocol, enabling plug-ins to be written
for home automation toolkits. AlertMe is a closed system
with a low cost subscription, but it can export its data to
Google PowerMeter and Google have recently announced
an API offering programmatic access to the data.

Research prototypes
In the recent research literature, sensor networks have been
used to accomplish fine-grained appliance level sensing and
control. Jiang et al.’s ‘ACme’ [14] consists of a wireless Epic
(Open Mote Platform) module with an energy metering IC
to provide real, reactive and apparent power measurements,
with optional control of attached appliance. The ACme hard
ware schematics and software are both open source.

Kim’s ViridiScope [15] (currently using Crossbow MicaZ
wireless sensor nodes that run TinyOS, HMC1002 magnetic
sensors and MTS310 sensor boards) follows a different path:
rather than conventional inline (effectively in-circuit) sens
ing, the authors use indirect sensing, with the attendant chal
lenge of estimating power consumption from observing 2nd
order effects of appliance use, such as magnetic fields, light
and so on. This intriguing approach is less cumbersome and
easier to deploy, but requires sufficiently dense deployments,
is potentially less accurate and is naturally unable to offer
actuation.

Algorithms
As Jiang et al. points out in their SenSys 2009 paper, “Mod
ern electronic devices are a composition of many sub-com
ponents. These multi-component, multi-state devices have dis
tinguished power traces per state that uniquely identifies
them”. Identifying the appliances in use from analysing tran
sients on the power line and their power signatures is in fact
not a new one: ‘Noninvasive Load Monitoring’ (NILM)
was invented by Hart, Kern and Schwepe at MIT in the early
1980s (U.S. Patent #4,858,141), they later provided a
reference summary [12]. Traditional NILM uses a single
digital AC monitor attached to the domestic power supply.
An edge detector picks up changes in voltage and current
which are then clustered on a 2D space of real against re
active power. Positive and negative clusters of similar mag
itude are paired (i.e. different appliances being turned on
and off)—two appliances with the same total power can still
be discriminated by differences in their complex impedance.

10http://www.google.com/powermeter
11http://www.microsoft-hohm.com
12http://www.maartendamen.com/?p=89
13http://blog.google.org/2010/03/google-powermeter-api-introduced-for.html
The approach is sensitive enough to tell devices with the same nominal rating (e.g. lightbulbs) apart due to their natural variation. Appliances with multiple components are modelled as state-machines rather than base components (motors, heaters etc.). The ease with which such systems can be deployed, especially by outside agents such as utility companies or unobtrusively inside smart meters, and the revealing level of detail of information yields naturally raises privacy concerns.

Hart’s steady-state approach is highly effective in home and small business environments where the number of concurrent events is low and there is low noise in the system. In later work, Laughman et al. [16] extends NILM to deal with more complex electrical environments (e.g. large businesses): higher harmonics in the aggregate current signal are used to distinguish loads with overlapping clusters and the distinctive shape of load transients are used to help recognise individual loads. We also direct the reader to Patel et al.’s 2007 paper which shows how machine learning techniques can be used to classify electrical events in the home from electrical noise (transients) with a success rate of 85-90% [22].

Heating and ventilation is one of the major energy impacts in the home. Understanding the thermal performance of buildings is important for anticipating energy use and calibrating for seasonal (e.g. outdoor temperature) effects. Rather than modelling the detailed structure and thermal properties of a given building, in his 1977 paper [26], Sonderegger proposed and experimentally validated an elegant approach based on six equivalent thermal parameters (equivalent thermal mass, equivalent solar window area, furnace field effect and three transfer constants between indoors, a “temperature clamp” and the house structure). The approach was found to enable accurate hour-by-hour estimates of internal temperature in different weather situations for the house for which they were experimentally determined.

**Practical Lessons from Home Automation**

In their 1990 paper, Newborough and Probert postulate how one might target major electrical appliances to help regulate peak power demand (PPD) [21], highlighting opportunities for smarter control and automation. The authors flag challenges for a lower energy future including low-rates of replacement of major appliances, low financial incentives for manufacturers to produce lower energy consuming appliances, and (in the UK at least) sociological notions of comfort, affluence and expectation of always available plentiful energy. They motivate opportunities for unobtrusive load-management across appliances, including shedding loads on a ‘least-necessary’ hierarchical basis: freezer’s compressors can be switched off for up to 30 minutes without apparent inconvenience; with well insulated water storage, hot water can be heated up during off peak periods rather than on demand, without compromising the consumer experience; appliances with regular demand curves can be energised (time-shifted) to off peak times of the day; certain appliances can be powered off (rather than left on standby) when rooms are empty for a certain period; and abnormal/excessive loads can be flagged to develop more energy conscious attitudes.

Something of this is seen in the work of Mozer’s Neural-Network House, which aimed to automatically program the house to optimise its systems for its occupants—although environmental impact was not their principal driver.

When considering automation of domestic systems it would be unreasonable not to mention the dedication and achievements of hobbyist home automators, who have been working on monitoring and reducing home energy consumption since the 1980’s. A wide range of standards, products and ad-hoc solutions that have grown up to service the needs of domestic and commercial building and appliance automators that should be extremely useful for those developing new ubicomp technologies. As starting points we direct the interested reader to a sophisticated example of home automation and real-time on-line reporting [http://bwired.nl], and portals designed for the home automation community: [http://www.automatedhome.co.uk](http://www.automatedhome.co.uk) and [http://homeautomation.com](http://homeautomation.com).

**ECONOMICS AND THE “ENERGY GAP”**

The research area of economics has examined energy consumption not only in terms of optimal pricing to individuals and industry, but also in coming up with solutions outside of direct pricing. The goal is to provide directions for public policy and regulation to create energy markets which function in a way which is beneficial for society in the long term. Since the late 1970’s, economists have been investigating why rational economic models can often fail to predict how individuals and large organisations will respond to economic incentives to reduce consumption [6].

This mismatch between rational-economic efficiency and real behaviour became known as the “energy gap”. Jaffe and Stavins [13] classify explanations of the “energy gap” into two categories: (1) market failures which keep actors from making optimal decisions (such as a lack of information about efficient appliances, or when the principal user of the energy is not the one paying for it directly); and (2) non-market failures, including uncertainty about future energy prices, or qualitative attributes (e.g. some people find incandescent lighting favourable to flourescent). In the 1990’s, some economists described the various types of failures using “barrier models”, which explained why certain actors are blocked from taking rational decisions regarding energy consumption in specific cases [29].

In addition to the exploration of failures causing the “energy gap”, there is the concern that the impact of energy consumption is not accounted for in the price of energy. In other words, the cost to the purchaser or user of the energy is much lower than the actual cost to society. Of course, the total societal cost is prohibitively difficult to assess—it requires reliable estimates of elements such as existing energy reserves, and future environmental conditions (such as climate change). An alternative approach is to compare current consumption and expectations for energy, to the energy that is likely to be available in the long term. David MacKay provides a highly accessible introduction offering a ‘balance sheet’ between our reasonable expectations for consump-
Some types of policy have been in place for some time in many nations, such as information for potential purchasers about the energy implications of their decisions. These include prominently displayed ratings for domestic appliances, and public bodies which provide advice to those renovating or upgrading their home building or infrastructure. However, even when accurate information is made available, it is often the case that actors will choose less efficient investments. These fall into the category of non-market failures, and have been referred to in economics as “behavioural failures”. A wide variety of behavioural failures have been described, such as biases towards 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”) [10]. While “behavioural failures” in economics are founded on strong observations about individuals’ behaviour (from fields such as psychology and sociology), they are difficult to verify empirically at larger scales.

**SOCIAL PRACTICES**

A significant amount of work in sociology has dealt with observing and analysing people’s routine practices (such as cooking, bathing, and cleaning), and how such practices have come to be. Sociologists have taken this rich data, and used it as a lens to understand the influence of people’s practices on energy. Personal and domestic consumption is heavily mediated by factors other than financial economy and personal preference: technology affordances, the built environment and infrastructure, and socio-cultural norms [30].

In this context of both individual behaviour and socio-technical approaches, Tracey Crosbie [4] has provided a review of home energy consumption. As she points out, there are well over thirty years of quantitative study, much of it aimed at behaviour modelling, and a much smaller amount of more recent, socio-technical qualitative studies. Crosbie calls for an integration of these historically distinct types of enquiry; studies will be most powerful when the longitudinal and detailed measurements associated with consumer and behaviour work is combined with the nuanced and detailed accounts given by sociology and ethnography of people’s everyday practices. Similarly, Wilson and Dowlatabadi [31] have called for a reconciling of individual behaviour-based models, and socio-technical ones.

Clearly, studying and modelling human behaviour can inform aspects of design [9], but it is important to bear in mind that casting consumption as an individual behaviour tends to imply that people make completely sovereign choices. This can result in ignoring or missing the effect of social expectations. For example, “persuasive” technologies with the intended goal of behaviour change can have minimal impact, when the practices they try to influence are heavily determined not by the availability of information or an individual’s personal preferences, but rather 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.

As designers and practitioners of pervasive technologies and applications, we play a crucial role in validating, refining, and recreating the norms of consumption. This is especially true in the home, where a large proportion of consumption is determined by practices wrapped up in comfort and cleanliness. Approaches to consumption and practices are concisely outlined and critiqued by Elizabeth Shove [25], and should be required reading for anyone working on domestic consumption.

“IT IS A RIDDLE, WRAPPED IN A MYSTERY, INSIDE AN ENIGMA…”

Despite intensive efforts across a variety of fields for a number of 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.) Another reason is that over the years, the motivations for understanding consumption have changed, and the framing and focus of inquiry have evolved. Thus, both our motivations for solving the problem, and our understandings of the causes of the problem are constantly shifting.

A third reason that solutions elude us is that the results of studies can be highly context-dependent. As mentioned above, findings on domestic consumption are heavily dependent on socio-economic factors, country of residence, and culture. However, consumption is even less generalisable than that: findings are not necessarily transferable to the next application, next month, or next door.

Before we conclude, we would like to make the final point, following Crosbie [4] and others, that domestic energy consumption is all-too-often cast as an issue to be addressed by new technologies. With purely technological approaches, there is a focus on optimising efficiency, which obscures the core issue of reducing consumption. An example close to home is the wording used in the call for papers for this *IEEE Pervasive* special issue on “smart energy systems.” The call refers repeatedly to the problem of “energy management”, and the language used implies that favourable solutions are ones which are automated through technology; the future of energy is “minimally invasive”, “optimal” and “dynamically adaptive”. Equally, one can point to earlier sections of this article, where we used phrases such as “smarter control” and “without compromising the consumer experience”.

Such an exclusively technological framing can marginalise alternative yet synergistic approaches. Far from simply being more efficient and technologically superior, much deeper changes to ways of life (practices) will be required over the next few generations. One alternative to a fundamental shift in practices is to support the increasingly universalised standards for indoor environments (e.g. 20–22°C). Many would argue that such standards are unsustainable, especially when taken to a global scale [25]. The new technologies we create should be seen as enablers and co-conspirators to changes...
to practice. The more failure there is to embrace an evolution of practices in the right direction now, the more that dramatic changes in consumption become necessary in the future. As Garrett Hardin unforgivingly argued forty-two years ago, in any situation where many people share limited resources, increased coercion (e.g. regulatory or economic) will most likely be required, to avoid utter catastrophe [11].

There have been numerous calls, starting more than fifteen years ago, for multidisciplinary approaches to domestic energy. As a community, this is where pervasive computing researchers can truly shine. Rather than approaching the problem from any one particular discipline, one should carefully consider alternative data collection and analysis methodologies, and theoretical framings of energy consumption. To conclude, we have two key take-home messages:

- In addition to any initial approaches you may have—ethnography, socio-technical studies, sensing technology, algorithms, interaction design, or application deployment—it’s absolutely crucial to cast a wide net in your background reading. We hope that the references we’ve given make it an easier start. Have a look at a few older references, or ones from fields of study with which you might be less familiar. You may be surprised by what you find.

- Before doing any domestic deployments, involve those with other approaches—theoretical and methodological—to participate in the design and implementation of your study. As observed by Crosbie [4], 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.

REFERENCES


