Home Energy Conservation: Methods and Approaches

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ABSTRACT

Energy conservation is an increasingly critical aspect of sustainability efforts in the 21st century. Energy consumption in the residential sector is a particular concern, as cost and demand of household energy increase globally. Furthermore, the work towards increasing advocacy for sustainability must necessarily begin rooted in the awareness of average household consumers. These and other challenges motivate research in the area of home energy conservation. Some approaches focus on correcting the energy consuming habits and behaviors of householders by psychological feedback, goal setting and increasing general awareness. Others approach the problem from the systems point of view, by designing efficient energy consuming appliances to be automated, context aware and self-adjusting. By reviewing the literature, we provide an overview of the general methods and approaches towards home energy conservation. In particular, we discuss: the general psychological model used in changing human energy consuming habits, the problems and solutions in measuring household energy usage, and the attempts at automating household appliances and systems.

INTRODUCTION

One of the greatest threats to mankind in the modern age is damage to the life sustaining ecology around us. This has prompt growing global consciousness towards sustainability efforts, to secure the long term viability of human life. One crucial aspect of this movement is the responsible management of energy resources which drive every facet of modern life. Beyond the discussions of negative environmental impact (such as the greenhouse effect caused by the burning of fossil fuels) and the depletion of non-renewable energy, is the more basic concept of energy conservation. This refers to efforts in reducing energy consumption, usually via direct reduction of energy use or by increasing the efficiency of energy usage.

To develop global awareness for responsibility of energy conservation, change must necessarily begin at the level of the local community, in the average household, for the individual consumer. Furthermore, the household energy sector accounts for a significant proportion of overall energy usage (e.g. 22% in USA [10]). Such challenges motivate much work in the area of home energy conservation and many methodologies and approaches have been published over the years. While some of the work has specific contexts in mind, such as focusing on specific energy types (e.g. electricity vs. gas) or targeting specific householders (e.g. teenagers), all of the research in the area continue to have the same core motivation in mind: to reduce energy consumption in households.

The approaches in the area can be roughly divided into two common methodologies. One is particularly concerned with the long term behavior and habits of household energy consumers. The other is focused on the appliances and systems that use energy in the household. Where the focus is on the human aspects of energy consumption, the approach is necessarily based on psychological models and study of human behavior. On the systems and appliance side, the advances may take the form of low level technological breakthroughs allowing the hardware to operate with more efficiency. A higher level approach attempts to give appliances and systems more intelligence and awareness of its operational context. In this paper we are concerned with the work centered on the human context, namely the psychological studies of human behavior, and the high level systems approaches that try to intelligently adjust appliances in response to human activity.

In the following sections, we review recent work in household energy conservation. First we review work examining the human condition and how it fits into the context of energy conservation, through goal setting behavior, feedback and interaction habits. This will establish the context and motivations for many implementation solutions. Next we review innovative ways to measure and manage energy consumption, in order to support psychological feedback. Finally, we look into recent solutions to automating energy consuming systems in the household, such as heating. We conclude with the common problems and general solutions distilled from the overall field of research, and suggest directions for future work.

THE HUMAN CONTEXT

For household consumers, sustainable energy consumption can be roughly achieved with two general strategies: using renewable or environmentally friendly sources of energy and consciously choosing appliances and their method and duration of use with conservation in mind. The second method entails an understanding of the human condition, the motivations and habits of householders and psychological methodologies for changing behavior. Research in this area is grounded in studying psychological theories and applying qualitative studies on targeted groups, i.e. different types of householders.

Feedback

One common idea for supporting household energy conservation is by improving feedback on the energy usage. It seems to be common sense that if there is greater feedback for energy consumption, it will more strongly reinforce energy conserving behavior. However in reality, feedback of consumption is not straightforward, as it is abstract, invisible and untouchable [5]. It is not like other consumer goods as it is not consumed directly but is rather involved in a wide variety of household activities, from preserving and cooking food, to cleaning clothes, enabling electronic entertainment such as TV and music and providing heating, cooling and ventilation. It is therefore difficult for consumers to accurately gauge their energy consumption and thus develop a coherent frame of energy conservation. Simple feedback such as the monthly bill do not reflect the specifics of what appliances or activities contributed to the resulting costs and therefore do not motivate any specific actions beyond a general desire to reduce costs.

The factors involving feedback and the various forms and features that enable it to be successfully applied to energy consumption was explored in work by Fischer [5]. First, a psychological model was presented to explain how feedback works in reducing electricity consumption. The model divided human action into two distinguishable types: habitual behavior and conscious decisions. In short, electricity consuming activities are mainly habitual, for example consumers do not consciously think when switching on lights at night. When presented with the feedback of the energy consumption data, it elicits conscious thoughts towards the activity, which manifests in a reevaluation of their behavior. Feedback increases the self-awareness of consumer actions, and the more closely the result of electricity consumption is reflected back to the consumer (e.g. through a direct display) the more relevant their behavior appears to them. Feedback can also be framed in different ways which promote different motivations, such as reducing personal costs versus reducing environmental impact. From this model, Fischer deduces the following requirements for effective feedback: captures consumer attention, links specific actions to effects and activates various motives that appeal to different consumer types such as cost saving vs. environmental consideration.

A literature survey was also conducted in [5] which explored international experiences of presenting feedback in household energy conservation. The results seemed to support the author's hypothesized requirements, namely the need to capture consumer attention as an important requirement to effective feedback. Other important features to be considered were: frequency and duration of feedback elicitation, appliance specific breakdown of data, clear and creative presentation and usage of interactive computerized tools.

Goal Setting

Another way of thinking about consumer action is by looking at the goals that they set. Goal setting is a psychological framework for understanding motivations and change of behavior [10]. When applied to energy conservation, it focuses on the type and form of energy conserving goals set by consumers, and how it affects their levels of motivation and ability to achieve set targets.

The two most important factors within the goal setting framework are the challenge and clarity of goals [10]. Studies have confirmed that difficult goals promote the highest level of effort and performance when the requirements and targets are clearly defined. On the other hand, vague goals lack specificity in requirements and increases variability in performance. For example a goal to reduce the usage of a TV by a set amount per week is more achievable than the general goal of being sustainability conscious. Other variable factors include the self-efficacy of individual consumers (measurement of perceived empowerment), which affect degree of goal commitment, response to negative feedback and tendency towards difficult goals. Feedback is also important to support goal achievement; feedback coupled with goals has proven to be more effective than having goals alone.

Based on these theories, [10] ran lab studies to explore how users make goal setting decisions. A pilot test was conducted, followed by a larger secondary test, based on detailed scenarios. Participants were presented with hypothetical energy conserving goals and scenarios involving different income families, and asked to choose goals for themselves and for the third party family. The results show that participants will choose specific and easy goals more often than vague and difficult goals and rate themselves to more likely commit to them. Participants also chose easy goals for themselves even if they are presented with feedback that shows it is ineffective in reducing energy usage.

The results of the study confirmed goal setting theory that people have more preference for goals perceived as easy and specific, sometimes even over goals that are known to be effective. This has implications for the design of interactive systems with the motivation of energy conservation: large and difficult goals that require long term commitment should be presented and supported iteratively. It also suggests the need for feedback that is specific and clearly presented to support the consumer desire for contextualized, specific goals that is solved by easy, actionable behavior.

Qualitative Study

Psychological theories are solid foundations to build on for research in the area of home energy conservation. However, they must be observed and evaluated in the real world to have any useful meaning. Qualitative studies of households yield real world examples of the motivations and problems of consumers in the context of energy conservation. They highlight examples of specific issues faced by consumers when attempting to conserve energy and create specific requirements for tools developed to support energy conservation.

One example of this kind of work is [2] which aimed to explore what kind of tools the ubiquitous computing community can develop for residential resource management. The ubiquitous computing community (Ubicomp) has long focused on energy conserving household environments, with the end goal towards creating intelligent homes that adapt to external and internal factors. With current levels of technology, this is already approaching possibility, but the question remains of what sorts of interaction methods, display and control systems are to be included in an intelligent resource conserving household.

[2] extends a previous study looking into sustainability conscious households, by examining average households that are not necessarily "green" conscious. The core of the work centers on a qualitative study of 15 households and their resource management practices with water, electricity and gas systems. Each house was physically examined and semi-structured interviews were conducted on the families that lived in each house. The resultant interview data was transcribed and coded into categories of related themes for analysis.

One of the findings from the analysis showed that some participants had made modifications to their homes and attempted to create good habits for energy conservation. The most common modifications were market available energy efficient light bulbs and programmable thermostats. The most common behavioral habits were turning lights off when not in use, unplugging unused devices or putting them on standby. These actions and behaviors show that it is common for households to take some energy conserving actions, as long as they were cheap or easily doable and provided a relatively large payoff in savings.

The analysis also summarized the motivations of householders who engaged in energy conservation activities as: desire for comfort, monetary reasons, and being environmentally friendly. The desire for comfort referred to things such as the ability to set thermostats to desired temperatures or having appliances operating in the right convenient setting, and not necessarily about energy efficiency. The motivation of cost is not reflected equally amongst family members as not all members are equally contributing to the monthly bill. For example children and teenagers in households not responsible for paying bills do not receive the relevant feedback from cost of energy consuming activities. Furthermore, consciousness of environmental factors was a comparatively weaker motivator and many participants thought they were already doing enough in this aspect. In general, since consumers had no meaningful way to compare their energy conserving activities to some national average, it was difficult for them to judge how effective their behaviors and actions were.

By far, the biggest issue confronting participants were difficulty in visualizing their resource consumption. There were several identified problems in this area, for example: the units of measurement of energy (e.g. kilowatts for electricity) was meaningless to consumers, lack of knowledge to judge the relative energy costs of different appliances, lack of real time feedback (billing data is only supplied monthly), no direct link of energy usage to financial and environmental impact, and lack of creative and fun ways to engage in conservation. In general participants complained that having no real time information to reflect energy consumption made it hard to determine the impact of their conservational actions and behavior. [2] concluded therefore that the challenge to the UbiComp community is improving the visibility of resource production and consumption costs, preferably via creative and attractive presentations.

[2] also warned of a potential divide between people who can afford technologies to support being energy conservative and those that cannot. Some emphasis must be put towards designing systems that are affordable and easy to implement for the majority of households. Another study [3], explores this potential divide by focusing on energy use in low income communities. Based in the U.S, where 30% of households live below the federal poverty line, the study focuses on low income households and their energy spending habits.

Low income households differ to affluent households in many ways. For example, low income households consume energy mostly on necessities (e.g. cooling, heating) while affluent households spend a greater percentage on luxury goods and appliances. Many low income households are also not responsible for paying their energy bills such as those renting or under government subsidized public housing. This means there is no direct financial incentive to be energy conservative for those households. Motivated by these and other factors, [3] conducted interviews with 26 low income households in two different locations in the US: a small town in southern U.S and a northerly metropolitan area.

One interesting result from the analysis of the interviews showed that despite participants not having financial incentive to be energy conservative, it did not stop them from trying to save it. The motivations identified for being energy conservative was spirituality, protecting the environment for future generations and prior training and habits. This is in contrast to the average household described by [2] that is mainly motivated by money and comfort and also households that identify as 'green', mainly motivated by cultural trends towards 'green' activism.

Other issues that limited energy conservatism were the lack of control over household infrastructure and decreased financial ability to afford efficient technologies. For example one participant had no control over adopting some home improvements because the landlord for the property would not approve of the changes. Other participants could not afford smart thermostats or energy efficient light bulbs. Furthermore, many participants raised the same concerns as average householders, that feedback for energy usage was nonexistent, not fine grained or in real time.

In summary, qualitative studies provide more of an in-depth and realistic picture of household energy consumption. Real examples of the problems and motivations for householders can be identified which generate more specific requirements for implementation. Results from different studies show that motivations and requirements do not necessarily generalize over all sectors of households with different socio-economic backgrounds. However, there exists a seemingly universal desire by householders: faster and more accurate feedback of energy consumption.

MEASURING ENERGY CONSUMPTION

In order to achieve effective feedback of energy consumption, the measurement of energy usage must be accurate and in real time. This has motivated a lot of work that attempts to make the management and measurement of energy usage more fine grained and easy to do. Here we look at 3 differing but related attempts to afford accurate measurements: a fine grained gas measurement technique, a circuit level electricity measuring system, and a contactless sensor measurement implementation.

In [4], the lack of attention given to gas usage over electricity in households is identified. Although gas meters exist commercially, they primarily operate in a way which do not produce instantaneous flow rate and therefore cannot afford real time feedback to householders. The work addresses this gap in research and proposes a new technique for gas power monitoring in room heating and hot water usage. The technique proposed uses several simple sensors attached to feeds going in and out of domestic gas boilers, measuring temperature changes as the boiler operates. This approach produces finer grained data as it measures individual appliance usage that are separated by copper pipes attached to the boiler (e.g. washing machine, shower, and bath). From a single household evaluation, [4] concluded their technique to be effective at obtaining fine grained measurements of gas heating energy. They also claimed the technique was easy to set up, affordable and accurate.

The broad motivation behind [4] has been aimed at reducing energy usage of teenagers in households. They identified the need to establish long term feedback reinforcement of consumption data in order to change behavior. This is typical of the motivations behind implementation research in this field, and mirrors the results of psychological theory and qualitative studies that identify accurate feedback as the key to reducing household energy consumption.

Another paper focused on the finer measurement of energy consumption is [8]. This paper identifies two main energy monitoring systems existing in households: whole home and device specific. Whole home systems are usually easy to set up and only require one energy meter. Changes in the overall power usage can be analyzed and mapped to certain appliances. However, this approach is not fine grained as only large appliances can be identified in fluctuating changes of total energy usage. Device specific approaches on the other hand usually require many meters to be set up and are more complex and expensive.

The technique developed in [8] is a compromise between the two main approaches, accomplished via the measurement of circuit level energy. Circuits separate the energy usage by locality, e.g. by room, which focuses the granularity of measurements to a few appliances as opposed to whole home measurements. Next, the technique uses a probabilistic level-based disaggregation algorithm which tries to identify and separate devices within circuits. This is made even more accurate via automatic training coupled with end system load controlling devices that identify change of device state. An initial evaluation showed that the technique operated with an average error rate of less than 5.35% for three devices on a circuit, with good response to changing device state. This approach allows finer, device specific energy feedback without the difficulty of installing dedicated energy meters for every device in the home.

A third approach [6] aimed to develop a technique which had comprehensive coverage of all appliances, fine grained measurements of each appliance, while being easy and affordable to install. The approach is a creative estimation technique based on the measurable emitted signals of electronic appliances, such as magnetic radiation, acoustic and light emissions. Using indirect sensors placed near a power line or appliance, the technique reduces the need to install monitoring devices in-line with electric wires. Coupled with an autonomous sensor calibration framework, the accuracy of the sensors can be increased by automatic calibration via a model based machine learning algorithm.

Energy measurement continues to one of the most critical components of energy conservation systems and approaches. Many more techniques exist and there is still ongoing work to improve energy measurement. The often cited challenges are the accuracy, speed and granularity of measurements and the ease of implementation and cost. Furthermore, just having the available data is often not enough to produce effective feedback; the way the data is presented to householders is also an important factor to consider, since in the end it is up to the householders to decide to act on the given data or not and how to go about it.

AUTOMATIC SYSTEMS

Another approach to home energy conservation is the automation of energy consuming systems. Unlike other approaches that rely on the eventual actions and behaviors of householders to enable energy conservation, automatic systems are not concerned with conscious human efforts which are prone to neglect and error. Instead, the focus shifts from the human aspect to the systems aspect and moves towards the development of intelligent self-correcting systems that are context aware and energy efficient.

Such a technique is proposed in [9] to automate the control of home heating systems via occupancy prediction. It identifies home heating as the highest energy consuming system in the household. Instead of leaving the control of a heating system to householders (such as via manually programmable thermostats) who may not have the best sense of energy efficiency, the system 'PreHeat', aims to automatically predict when heating should be turned on and off. The system was designed to reduce 'MissTime', the time which a house is occupied but not warmed, by sensing household occupancy and using historical data to estimate future usage.

Besides physical sensory hardware (such as temperature and motion sensors), at the heart of Preheat is a prediction algorithm, which reacts to occupants entering a room, and also predicts when an unoccupied room will next be used. The system and its algorithm was compared with 2 other algorithms, one which left heating turned on continuously, and another which emulated a statically pre- programmed scheduling thermostat. The evaluation showed that Preheat both reduced gas consumption and 'MissTime' when compared to the other conditions. The paper concluded that Preheat enabled efficient heating while removing the need for manual consumer control.

Other occupancy sensing techniques exist, such as in [7], which similarly uses motion sensors and prediction models to turn HVAC (Heating, ventilation and cooling) systems on and off. Evaluations showed that the approach on average saved approximately 28% more energy than existing approaches. Another example is [1], which uses data gathered by sensors in the household to build profiles of inhabitant behaviors and automatically controls system parameters to suit profiles. By deploying a wireless sensor network that is aware of presence of householders and physical parameters such as light and temperature, the system is able to modify system behavior according to changes in the environment.

These systems and approaches in general, attempt to automate the control of high energy consuming appliances in order to provide the required comfort level while operating most efficiently. When left to human control, systems may be too complex to manually adjust or inhabitants may simply choose to not operate them efficiently, out of lack of motivation or time. Work in this area help promote energy conservation in households that would otherwise be hindered by the difficulty of changing human habits and behaviors.

SUMMARY

In this paper we have looked at an overview of methods and approaches towards home energy conservation. We first explored psychological theories behind human habits and behavior and how feedback and goal setting can promote energy conservatism in householders. Next we identified some of the practical issues confronting householders when trying to be energy conservative by looking at qualitative studies on household inhabitants of different backgrounds. From these two areas of research, we saw that feedback of energy consumption data was the most critical component in promoting energy conservative behavior. For effective feedback, the measurement and display of energy usage must be accurate and in real time. This prompted some examples of research into fine grained energy usage measurements. Lastly, we briefly looked at examples of work developing intelligent self-correcting energy consuming systems that do not require manual human intervention.

FUTURE WORK

Due to the enormous scope of the topic, it is difficult to cover all aspects of research in home energy conservation. For example, some creative solutions to feedback such as pervasive game based systems have not been mentioned. Details of actual feedback interfaces and design patterns promoting sustainability have also not been explored. In general, the work presented here serves as a general survey of the literature and omits finer details of each case.

An alternative way to study the factors concerning home energy conservation would be to examine all stakeholders involved. Many of the studies presented here view energy consumption in homes within an internalized context. One exception was the qualitative studies on low income families that identified some householders being limited in their control of their situation due to external stakeholders (e.g. landlords, housing agency). Examples of external stakeholders include power companies, government agencies and the local community surrounding households. Deeper still is the social and cultural effects that influence householders such as education and upbringing or where they are in the world. The complex dynamics behind factors influencing household consumers ensure that much more work can be done to better understand how energy conservation can be supported.

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