AWARE@HOME: A CASE STUDY IN TECHNOLOGICAL DESIGN TO PROMOTE ENVIRONMENTAL CONSERVATION IN THE AMERICAN HOME

Andres Clarens, Antonio Vittorini, Brad Lamiman, Konstantinos Boukouris, John Pariseau, Prashanth Pandian, and Steven Skerlos[1]

ABSTRACT

This paper describes an inexpensive technology called AWARE@home that was designed for households to receive information regarding their utility consumption patterns through at-home wireless networks. Utility information devices have been proposed or developed in the past but to the authors' knowledge this is the first to be: 1) designed specifically for homeowners to facilitate choices regarding consumption 2) built on existing home wireless "WiFi" networks and 3) developed with retrofit sensors that do not require meter replacement. Given that AWARE@home is designed to empower consumers to save money and conserve resources, the technology was selected as a winner of the inaugural EPA P3 competition in 2005. The system is designed for minimal effort by consumers: first, a service professional installs the AWARE@home retrofit device onto the existing meters in a process that takes approximately 30 minutes. Then the consumer receives a startup kit that includes a CD and, if needed, a USB wireless antenna for the computer. After loading software from the CD onto the computer, the homeowner is asked basic questions about utility rates, billing cycles and how much he or she wants to spend on utilities each month. At any point in the month that the desired expenditure on utilities set by the consumer is likely to be exceeded, AWARE@home will send an e-mail message or pop-up window message providing a warning about this predicted over-spending on utilities. This paper describes the prototype AWARE@home system that was produced for the EPA P3 competition and later installed in the home of an author for further testing. The AWARE@home prototype meets a number of design specifications related to simplicity, reliability, and cost. It includes both hardware and software components for "Wi-Fi" monitoring and alerting of home water, gas, and electricity consumption. The prototype for electricity monitoring has been operating continuously for over eight months at a home in Ann Arbor, Michigan, it has consistently and securely relayed usage rates to the local utility, and it has reliably predicted, notified, and helped the consumers to avoid excess expenditures on electricity. Preliminary research conducted during this project has shown that a majority of homeowners responding to a marketing survey would be interested in owning AWARE@home to reduce monthly expenditures and/or environmental emissions.

KEYWORDS

energy efficiency, household consumption, environmental footprint

INTRODUCTION

Some of the most pressing environmental challenges facing industrialized nations today are the emissions of greenhouse gases, emissions of criteria air pollutants, and the depletion of energy resources. Consumers in these nations have disproportionately large environmental footprints resulting from their high standard of living as measured by gross national product. The United States, for instance, represents less than 5% of the world's population and consumes approximately 25% of its energy (Bishop 1999). Much of this consumption occurs in the home where residents consume about 20% of the electricity and natural gas consumed by the country as a whole (EIA 2000; NGSA 2005). Consequently, choices regarding utility consumption at the household level are major contributors to the world's energy use, water scarcity, and the production of waste. Moreover,

1. Department of Mechanical Engineering, The University of Michigan at Ann Arbor, aclarens@umich.edu.

small improvements in the way people use utilities at home could produce substantial reductions in the Nation's environmental emissions and resource consumption. For example, reducing energy consumption of all US refrigerators by just 1% would save approximately $140 million dollars in energy costs and 1.5 million tons of carbon released to the atmosphere each year (EIA 2004). According to the US DOE Energy Information Administration, this amount is on the same order as the total energy-related carbon emissions of East Africa (EIA 1999).

While there is a direct relationship between per capita energy consumption and gross national product of a country (WRI 1990), countries such as Denmark and Sweden that have very effective conservation programs have shown that it is possible to have a high GNP and relatively low per capita energy consumption (Bishop 1999). The comparison between European countries and the United States with respect to energy intensity and GNP indicates that a major component of the U.S. environmental footprint is based on customs and policies rather than quality of life (Schipper 1996). In Sweden for example, government tax schemes have provided disincentives for commuting in personal vehicles resulting in high density development. The lack of similar factors in the U.S. has led to greater sprawl, larger homes, and more reliance on automobiles for transportation (Gardner and Stern 1996). With continued increases in energy prices such as those observed in 2006 bound to affect the disposable income of homeowners, U.S. government policies and cultural norms will eventually need to adapt.

European studies have shown that demand side management such as electricity tax schemes, direct subsidies for efficiency improvements, and information programs are effective at significantly reducing electricity consumption. Recent work in Ireland reported on an information program that resulted in a national electricity savings as large as 7% (Dulleck and Kaufmann 2004). The authors concluded this was due to the fact that the electric utilities in Ireland were not in a position to act strategically (i.e., they could not create off-setting incentives for consumers to increase demand) and that the Irish population had a relatively low level of knowledge when the information program was initiated. Both of these conditions exist in the U.S. as evidenced by the energy crisis in California and the general lack of understanding surrounding the black-outs on the East Coast during the summer of 2003.

Awareness has been shown to play a major role in people's response to energy conservation in the home (Black, Stern et al. 1985). Research on consumers in Massachusetts attempted to understand the extent to which energy conservation efforts are influenced by internal factors (attitudes or awareness) or by external factors (income or house size). When barriers to action are high, (e.g. installing new insulation in a home) awareness of the environmental or economic impacts of consumption decisions matter little. When barriers are low (e.g. adjusting the thermostat) a small amount of awareness can go a long way to reduce consumption.

The heads of U.S. households are unlikely to become more efficient users of public utilities because the feedback loops are so large (e.g., the time it takes to get an energy bill or the effort required to quantify the financial benefit of energy conservation efforts). If a homeowner has kept the thermostat setting a few degrees warmer than it needs to be in February, during hours when he or she is not home, he or she may not look at the bill until late March when winter is over and nothing can be done to reverse the bill or the associated environmental impact.

Much of the pollution and waste caused by overconsumption in the home is avoidable, without significant technological change, just by affecting the behavior of individual citizens and consumers. For instance, the U.S. Environmental Protection Agency (EPA) reports that Americans spend $1 billion each year to power their TVs and VCRs when they are switched off (EPA 2004). In the U.S. alone, the electricity consumed by consumer electronics while they are off equals the annual output of 12 power plants (EPA 2004). Further, the average American household spends $1,400 per year on energy bills (EIA 2004). In a survey conducted for the EPA's Energy Star program, 93% of respondents believe in saving energy for the environment and their pocketbooks but don't know where to start (Blueair 2006).

In addition to curtailment behaviors, such as lowering the thermostat, homeowners would be more likely to invest in improved efficiency, such as installing insulation, if the benefits were immediately evident. Such investments have the potential to be more effective than curtailment because curtailment activities require maintenance over time and often involve self sacrifice. Curtailment efforts are often associated with reductions in quality of life: a homeowner can reduce their environmental footprint if they turn off their heat and wear a jacket indoors all winter. Large scale, one time, efficiency increasing actions are more appealing to homeowners because they do not generally entail a reduced quality of life. In addition, such actions generally do not require continuous investments of time and effort. Nevertheless, research on future discount rates suggests that homeowners are less likely to pursue these high capital cost investments in efficiency if the benefits are not evident in the short term. The barriers to replacing an old furnace with a high efficiency unit or buying the more expensive EPA Energy-Star television can be lowered if homeowners get more immediate feedback on their investments.

The relatively high demand placed by U.S. households on the environment is compounded by the fact that most U.S. homeowners do not know how their decisions impact utility delivery. Leaky water distribution lines, for example, mean that a gallon of water dripping from a faucet in the home translate into as much as two or three gallons treated at the water utility, all for water that is never used. Electricity consumption in the hot summer afternoons when air conditioners are running is another example. During these periods, power utilities are forced to fire-up mothballed and inefficient plants to meet peak consumer demands translating into large costs and environmental impacts. Our built infrastructure is designed so that people are highly *unaware* of the resource demands they are placing on society and the planet.

These facts create a clear opportunity to reduce environmental impact while freeing financial resources for less environmentally damaging investments in the economy. This paper describes a project called AWARE@home that has successfully developed technology that will serve to provide individual citizens and consumers the information that they need to modify their own behavior with respect to utility usage, saving money and protecting the planet at the same time. AWARE@home was designed to meet several important needs: 1) it is designed to be *installed on existing meters* 2) it can be used to *monitor electricity, water, and/or gas using a single software interface* 3) it is *intended for use by homeowners* to better manage their own utilities.

Several other research groups are working to develop similar tools for consumers to receive information about their utility usage. As part of a larger effort to design the "Duke-Delta Smart House" students and faculty at Duke University have developed an intelligent HVAC controller (SmartHouse 2006). The controller uses a neural network to train itself about the usage of the homes inhabitants so that it can recommend the most efficient consumption levels. The Duke controllers, however, are not intended to be installed in existing conventional homes and so have limited applicability in the residential sector in the short-term. This system does not include a monitoring system for water.

Researchers at the University of California-Berkeley have developed a smart thermostat designed primarily to ease the peak use demand placed on the California power grid during summer Air Conditioner season (CEC 2006). The device communicates wirelessly with electricity meters and with the utility company. It receives real time usage information and real time costing information that it can use to make optimal decisions about power consumption. The smart thermostat, however, is only focused on electricity and does not leverage existing personal computer and wireless communications capabilities to monitor all utilities.

Some industrial suppliers are also pursuing technology to provide utility companies with real time consumption information. Advanced Metering Data Systems (Covington, LA) is making utility meters that transmit consumption information to radio towers and then relay that information on to utility companies (AMDS 2006). The advantage for the utilities is that no vehicle would need to drive by to collect consumption data. AMDS is currently working on several pilot projects with utilities across the country to test their product. Of the three examples, the AMDS technology is the closest to implementation but unfortunately it does not engage homeowners in the monitoring process. So although it will provide utility companies with more real time consumption data, homeowners cannot use that information to make better choices without specific consumer advocating action being taken by utility providers to reduce their own revenue.

The AWARE@home concept combines some of the elements of these other academic and industrial efforts to produce a wireless utility monitoring device for the U.S. home. The tool is intended for use by homeowners rather than a utility company. It can, however, be used to receive/transmit data between the home and the utility via broadband lines to update rate information and provide the utility company with real-time consumption data. Most importantly the technology is PC-based so that it is inexpensive, easy to install, and simple to use.

OBJECTIVES AND PROJECT VISION

The goal of the AWARE@home project is: *to provide consumers the means to monitor their own expenditures on utilities (e.g., water, gas, electricity) over a wireless network without having to invest more than 5 minutes of effort per month.* The overall concept is illustrated in Figure 1. The authors have accomplished this vision by 1) developing wireless transmission technology for conventional water, gas, and electricity meters that can communicate on standard 802.11 wireless networks, 2) developing software that allows the meters to send an email or "pop-up window" to the consumer's computer when utility consumption exceeds a target level in dollars that is defined by the user, and 3) providing the means for homeowners to track and plot their utility consumption in the same way many people plot their own financial investments in the stock market.

In practice, the AWARE@home system is to be implemented in the following way:

Step 1: A utility technician installs an AWARE@home wireless transmission device to the water, gas, and electricity meters. The retrofit

FIGURE 1. Conceptual illustration of the AWARE@home system. Digital flowmeters, microprocessors, and wireless transmitters are incorporated within existing metering technologies (gas, electric, water) so that consumption data and alarms can be sent to an in-home personal computer. Also shown is a wireless meter that can communicate the electricity consumption of individual appliances "plugged in to the wall" to the AWARE@home system.

hardware is robust, simple, and inexpensive – simply the cost of the wirelesss communication, microcontroller, added memory, and antenna. Pilot installation for the prototype system took about 30 minutes for the electricity meter and can be reduced in the future.

Step 2: The consumer receives a start-up kit for the AWARE@home system. If the consumer does not already have a home wireless network, then the kit will contain a USB-compatible transmitter/receiver (these are already available for $20-$30 commercially) and a CD containing the AWARE@home software. If the consumer already has a home wireless network, then he or she would download the AWARE@home software free from the Internet. The AWARE@home meters show up on the home network just as any wireless device does, except that the meters require a secure password connection for communication.

Step 3: The consumer runs the installation program for AWARE@home. The user is first asked to input his or her security code that ties the user to the particular meters to be monitored. This security code is necessary to assure that no one other than the utility provider and the consumer can access the data stored within the meter. Then the user is asked to input the price of electricity, gas, or water per unit consumed (e.g., 8.5 cents per kilowatt hour for electricity). The user is also asked to input either the maximum amount of money per month that he or she would like to spend total on utilities, or the maximum amount of money that he or she would like to spend on each of the individual utilities: gas, electricity, or water. For discussion purposes here, we will assume that the user has selected to pay no more than $220 per month for all utilities combined.

Step 4: Consumer does nothing else. The AWARE@home system monitors and accumulates utility usage rates without any interaction with the user. Only if the consumer is en route to spend more than $220 in the given month will the user be notified. The system sends an email, and/or generates a pop-up window on the screen of the computer next time it is turned on.

Step 5: Consumers have the option to ignore this information, but it is likely that someone who purchases an AWARE@home system would at least be motivated to recover the cost of the system. This could lead to better long-term consumption habits. Moreover, after receiving alerts several months consecutively, the probability of consumers taking action to reduce consumption and to share conservation strategies with others grows. A future objective of this work is to link the system with "smart tips" available to users on the internet.

APPROACH AND SPECIFICATIONS

A number of high-level engineering design requirements were used to develop the AWARE@home prototype. These requirements, which are listed below, describe the broad characteristics of the system:

- **Simple to use.** The computer interface has both basic and advanced functions to be selected by the user. The installation process is simple and quick. A utility professional can install the hardware in under 30 minutes and the homeowner can install the software in under 5 minutes. Direct monthly interaction with the system is not required to be more than a few minutes.
- **Robust, durable design compatible with existing water, gas, and electricity utility meters.** The analog-to-digital signal conversion designs utilized in the AWARE@home are conceptually simple, reliable, and inexpensive so as to facilitate diffusion of the technology into existing meters at minimum cost. This is made possible through the use of hall effect sensors as described below.
- **Wireless and FCC compliant.** Installation requires no wires to the host computer. Wires are only necessary within the utility meter for sensor and power connections between the meter, and for connecting the microprocessor with the wireless transmitter/antenna. The wireless module complies entirely with FCC Part 15 Class B. The system is fully operational even in the presence of electromagnetic interference present in the home, at distances exceeding 100 feet.
- **Stores data without computer.** The microprocessor must process information and store it in case

a power outage has occurred. It contains a battery and data integrity up to 256 Kb.

- The environmental emissions associated with AWARE@home production and use are insignificant relative to the environmental emissions reductions achieved through the expected use of the system.

Over the course of academic year 2004-2005, 20 University of Michigan (UM) students were involved with the AWARE@home hardware and software system design, prototyping, and validation. These students were from three courses in the UM College of Engineering: ME 589: EcoDesign and Manufacturing (http://www.engin.umich.edu/labs/EAST/me589), ME 450: Capstone Senior Design and Manufacturing Course in Mechanical Engineering (http://design.engin.umich.edu), and ENG 490: Engineering for Community.

The process began by benchmarking existing products. While the authors found several systems that allow at-home meters to communicate with utility companies (e.g., using modems and cell phone towers), no existing system was found to be compatible with standard 802.11 wireless protocols that would permit personal computers inside the home to directly access the data. Similarly, electricity consumption meters for appliances are commercially available (e.g., Watts Up?), however these meters lack a wireless capability. Based on the gaps identified in the market, the concept for the AWARE@home system, including water, gas, electricity, and appliance meters, was developed as shown in Figure 2. The following paragraphs describe additional technological specifications for these products that were established during the project.

Electric, Water & Gas Meters. The most important customer requirements and engineering specifications for the electric, water, and gas meters are summarized in Table 1. The engineering specifications were determined by making sure all customer requirements were met by at least one specification. The requirements were established through consumer interviews, marketing surveys, as well as discussion and brainstorming amongst the design team.

Appliance Meter. The customer requirements and engineering specifications for the appliance meter are summarized in Table 2.

FIGURE 2. Concept schematic displaying the principal components of the AWARE@home system: water, electric, gas meter translators, appliance meter with 802.11b wireless capabilities and PC interface.

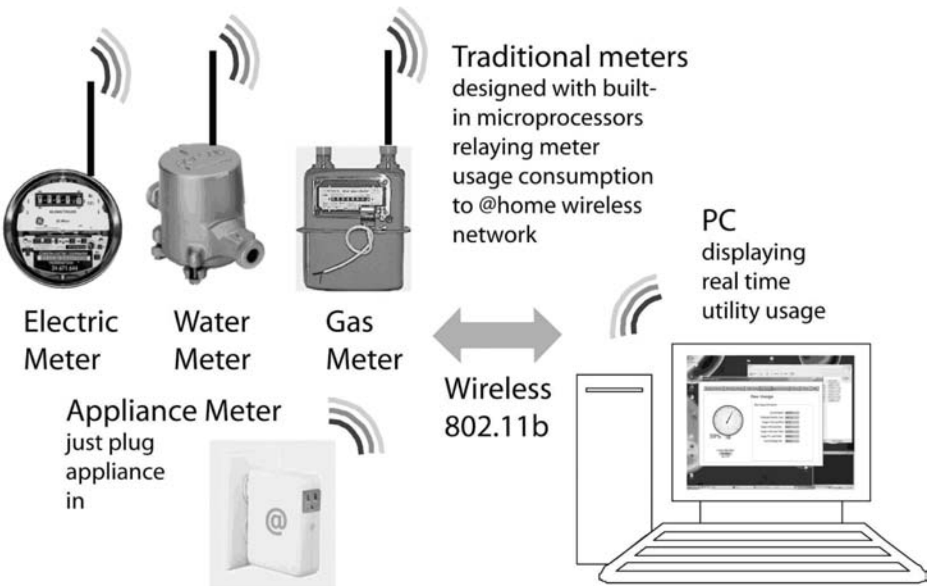


TABLE 1. Most important customer requirements and specifications for the electric, water and gas meters.

Customer Requirements	Engineering Specifications	Target
Accurate measurements	Relative error of measurements (%)	5
Reliable system	Lifetime of system (years)	50
	Data Storage w/o Computer Turn-On (days)	90
Fast installation	Time to install (hours)	1
Low maintenance	Back-up battery life (years)	3
Inexpensive	Manufacturing cost ($)	15
Able to be retrofit to house	Fraction of existing meters compliant (%)	90
Use During Power Outage	Battery run time (days)	30

Compact Appliance Meter. The wireless appliance monitoring unit was designed to occupy a volume of less than 0.25 ft^3. While the prototype did not achieve this small footprint, the commercialization of the design could achieve such a small volume. Competing designs such as the Watts Up? and Kill-A-Watt (WattsUp? 2006) occupy about 0.25 ft^3, but do not feature wireless capabilities. For the prototype made in this project, an increased efficiency in circuit board and component layout and removing the digital display would allow the design target to be achieved.

Easy Installation of Wireless Appliance Electricity Consumption Meter. In addition to wireless-to-PC monitoring of water, gas, and electricity consumption from the retrofitted meters, we designed and prototyped a real time electricity monitoring system for appliances that is also integrated to the AWARE@home system software. The installation time by the consumer for this device was set to be at most 10 minutes. This installation time refers to the time required for the homeowner to set up and start the appliance monitoring system, and to verify its ability to communicate with the AWARE@home software. In the final system, this simply involved plugging the appliance into the device, plugging the wireless device into the wall, and then running the set-up software for the AWARE@home system.

Power, Current, Voltage, and Temp. Operating Ranges for Wireless Appliance Meter. It was specified that the appliance meter should be able to meas-

TABLE 2. Most important customer requirements and engineering specifications for the wireless electricity consumption appliance meter

Customer Requirements	Engineering Specifications	Target
Reasonable size	Maximum occupying volume (ft^3)	0.25
Quick installation	Time to install (minutes)	10
Safe installation and use	Amount of electronics exposed (%)	0
	Wires cut during installation (#)	0
	Waterproof	Yes
Inexpensive	Manufacturing cost ($)	15
FCC/IEE compliant	Meets regulations and requirements (%)	100
Durable	Maximum height of drop (ft)	4
Robust shielding from outside	Operating temperature range (°C)	50–400
Able to monitor regular appliances	Operating voltage range (V)	110–125
	Operating frequency range (Hz)	60
	Maximum power measured (W)	2000
	Maximum current measured (Amp)	20
	Maximum power consumed (W)	1500
Accurate measurements	Relative error of measurements (%)	5
	Maximum resolution of measurements (kWh)	0.1

ure up to 2000W power and 20 A current. Also it was designed to monitor voltage ranging from 110-125 V (USA operation) and doing so in temperatures ranging from 0 to 80 °C. 2000W and 20A were selected as maximum power and current since most home appliances (excluding heavy duty ones such as clothes dryer and oven not plugged into ordinary household outlets) use only up to 1500 W and most outlet fuses in the home are 20A or less.

Accuracy of Measurements. It was specified that the relative error of measurements should not exceed 5%. Also, the resolution of power measurements should be 0.1 W or less.

Microcontroller Requirements. Microcontroller requirements are listed in Table 3.

Based on these requirements and specifications, the students generated a large number of specific technical design concepts for:

- Analog-to-digital conversion of meter measurements;
- Consumption data processing, storage, backup, and wireless transmission;
- System power backup;
- Predictive alerting algorithms;
- Software design, calculation capability, and interface.

These concepts were modified and optimized as necessary to be maximally compatible with water, gas, and electricity meters commonly found on the market today. The concepts were then evaluated, finalized, and prototyped. Concurrently, students from the Steven M. Ross School of Business at the University of Michigan performed an initial assessment regarding user interaction and habits related to utility usage as part of the course MKT 617: Marketing Research Design and Analysis.

Marketing Research. A market survey was conducted to 1) assess interest in a technology such as AWARE@home 2) understand consumer preferences and 3) determine potential product features. An online survey was developed with 26 questions that included general demographic, behavior, and attitude questions as well as specific questions about consumer preferences in a proposed product. The survey was sent to 20,000 email addresses and received 376 respondents which represented a normal response rate for online surveys. The approach has intrinsic biases which should be considered when interpreting the data. The survey respondents were by and large educated, high income, computer literate, young adults and over 60% of respondents owned their primary residence. While acknowledging that this breakdown is not representative of the US in general, it is notable that a large majority (75.7%) indicated an interest in a device such as AWARE@home. Of the affirmative respondents, 21.1% were interested in the technology strictly because they have a deep conviction for protecting the environment and have interest pursuing technologies that allow them to lessen their environmental footprint. 36.1% of the respondents were interested in conserving energy and protecting the environment and would be interested in such a technology if it was inexpensive and easy to use. A third type of homeowner (18.5%) was interested in the technology strictly for the monetary savings associated with energy conservation.

A number of recommendations emerged from the marketing research efforts. Many of these are reflected in the specifications listed earlier (e.g., should require 15 minutes or less per week to operate, deliver consumption information through e-mail, etc). When asked to rate product features, the respondents across the board ranked their preferences in the following order: cost savings > ease of use > time required to install > ease of installation > product features. The survey respondents also felt strongly that

TABLE 3. Customer requirements and engineering specifications for the microcontroller

Customer Requirements	Engineering Specifications	Target
Wireless	Use on home network	802.11b
Unobtrusive	Built-in to meter	Yes
FCC/IEE compliant	Meets regulations and requirements (%)	100
Stores Data w/out Computer	All data sent when requested by computer	Yes
Computer Interface	One click install	Yes

privacy of data would need to be strictly maintained in order to make the technology viable.

RESULTS AND FINDINGS

There were three key developmental accomplishments involved with the successful development of AWARE@home:

1. It was necessary first to develop the *AWARE@home signal processing and communication board* that, in its commercial implementation, would become the printed wiring circuit board that would be common to all the meters. This board, which in its prototype form is actually a box of assembled off-the-shelf components, receives, accumulates, stores, and processes data from the metering actuators. The board must also store the information in the event of a power failure. For the water and gas meters, where no readily available electricity supply exists, the board must be self-powered (e.g., using a solar panel or battery storage of small quantities of sel-generated hydropower). The system board communicates over an 802.11x wireless network with the user's computer. The system sends alarms as needed to the computer, which then alerts the user via email or a pop-up window. The prototype AWARE@home signal processing and communication system is shown in Figure 3.
2. It was necessary to find a way to convert existing dial-style analog meter actuators to digital signals that could be understood by the AWARE@home circuit board. The goal here was to minimize design changes to existing metering technology with the aim of minimizing the cost to "add-on" wireless capability to meters already being sent to the field by utility providers so that their employees can receive consumption data and billing information without visiting the home (e.g., using modems and cell phone towers). This can be achieved in much the same way as TiVo inc. (Alviso, CA) achieves its 2-way communication with consumers utilizing existing communications systems (e.g., Wi-Fi, telephone) in the home.
3. It was necessary to develop software for the user's computer that could detail consumption relative to targets as desired. The software would not only be responsible for the pop-up window but if user were to click "details", he or she would see a plot such as Figure 4 and in the future be directed to a

FIGURE 3. The outside (left) and inside (right) of the AWARE@home signal processing and communication board in its prototype form. Commercial implementation could reduce its volume by a factor greater than 10.

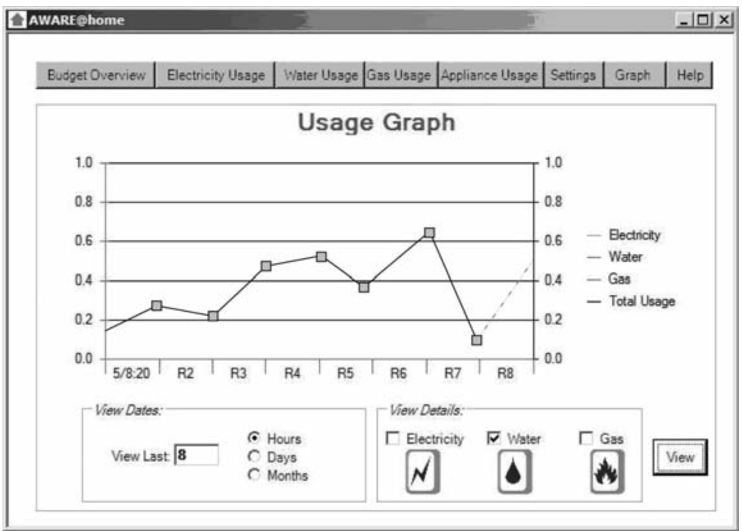


FIGURE 4. Sample user display illustrating water consumption as communicated by the wireless meter developed during the AWARE@home project.

website that would provide general information regarding how to reduce the consumption of the specific utilities of interest. During future work, a website similar to "*i*fit.com" is envisioned where one could access customizable guidelines for reducing utility consumption. A blog-style environment might also be useful for users to share experiences with AWARE@home and the financial/environmental benefits of reducing the consumption of utilities.

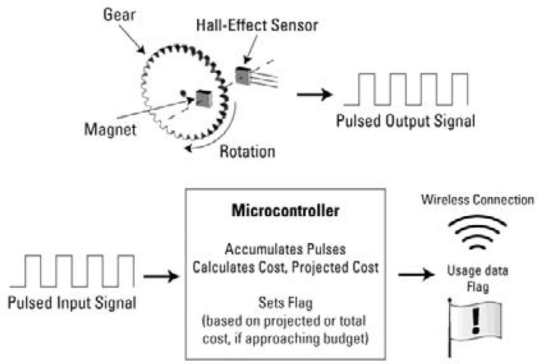
At the conclusion of the project, a fully functional AWARE@home system was prototyped. The meters proved their capability to monitor the household consumption of gas, electricity, and water, as well as the electricity consumption of individual appliances. It was also shown that this information could be communicated over standard WiFi protocols used by home computers and interpreted by the AWARE@home software program. The wireless gas, water, and electricity meter prototypes are shown in Figure 5.

The following sections describe the design of each of the individual components in the AWARE@home system in more detail:

Hall Effect Sensors. In the initial AWARE@home prototype, widely utilized gas, water, and electricity meters (Figure 5) were retrofitted with hall-effect transducers to convert the analog dial meter actuators to digital signals. In all of these meters, a mechanical system of gears and shafts drives the odometer read-outs which display the amount of utility usage. In the electricity and gas meters, the design involved attaching small magnets to one of the rotating gears and mounting the hall-effect sensor in a way that it could read the changing magnetic field of the rotating magnet as shown in Figure 6 (top). Since the water meter already had a rotating magnet as part of its design, it was only necessary to install a hall-effect sensor to read the existing magnet. The pulsed output signal from the hall effect sensors are then processed by the microcontroller found on the AWARE@home circuit board as shown in Figure 6 (bottom).

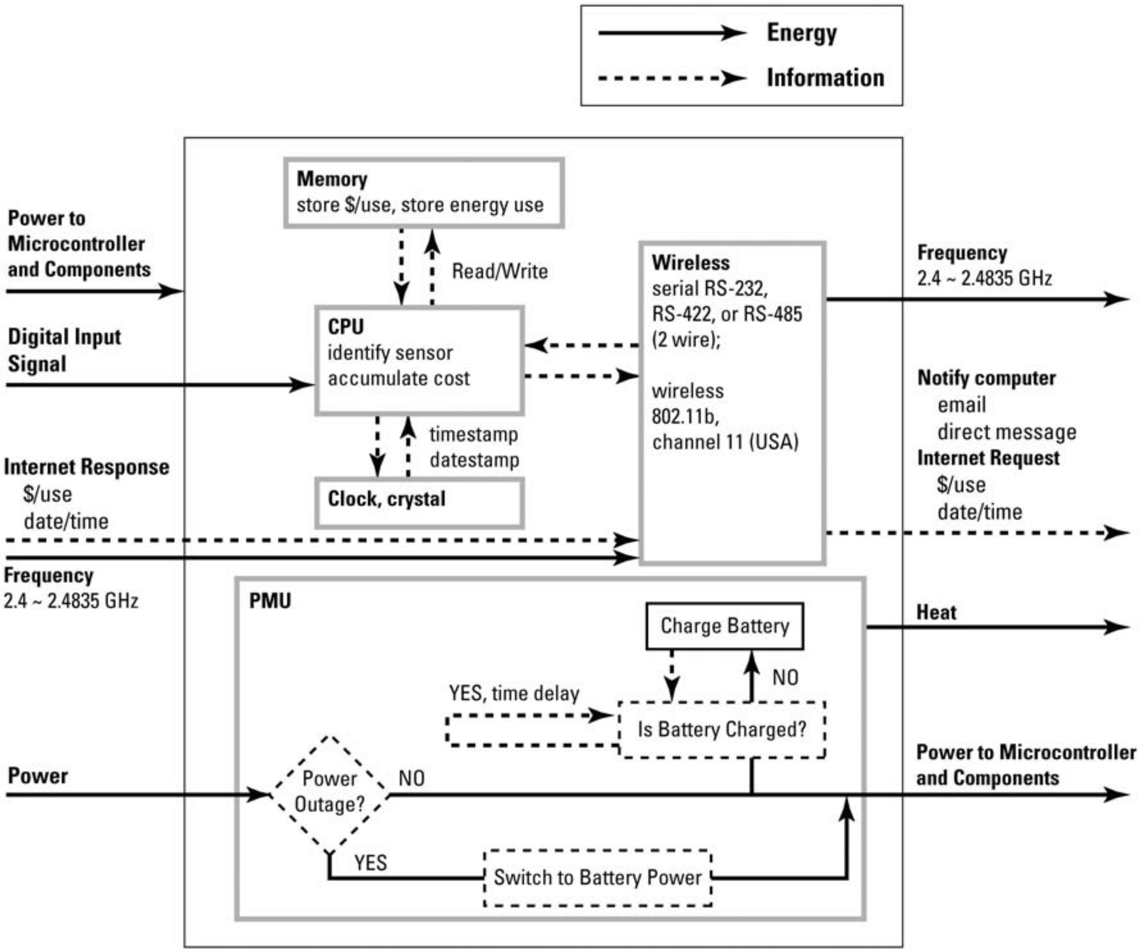
FIGURE 5. Working prototype water (left), electricity (center), and gas (right) meters developed for the AWARE@home system.

FIGURE 6. Magnet and hall-effect sensor setup used for electricity, gas, and water meters (top) incorporated to existing meters as shown in Figure 8. The pulsed output is read by the microcontroller (bottom) where the signals are processed, interpreted, and communicated with the AWARE@home software running on the at-home personal computer using 802.11 wireless protocol.



Microprocessor. A microcontroller was necessary within each meter to accumulate the consumption data output by the hall effect sensor, interpret the data, and relay high-level consumption information to the in-home computer. Hall effect sensors were used to capture usage information from the meters. An Axiom CML-9S12DP256 development board was utilized for this purpose, along with a real time clock chip made by Maxim IC/Dallas Semiconductor used to time stamp the data. A wireless-to-serial adapter, made by DPAC Technologies, was used to send data over an 802.11x network using the serial port on the development board. A block-diagram of the prototyped system is presented in Figure 7. The design shown in Figure 3 has an LCD screen and a keypad so that during installation, a homeowner or utility professional could be prompted to answer a few simple questions such as the time/date and utility cost. In future designs, this information could be

FIGURE 7. Functional decomposition of the AWARE@home signal processing and transmission unit included in each of the utility meters and the appliance meter.



input through the computer interface to keep the individual meters inexpensive to manufacture.

Water Metering. The analog-to-digital conversion as shown in Figure 6 was achieved within a Sensus SRII water meter. This water meter was selected because it is representative of most common analog water meters used in U.S. homes. In the design, a hall-effect sensor is mounted next to an enclosure where a circular magnetic rotates on the needle of the meter. The sensor detects changes in the strength of the magnetic field as the magnet rotates, registering each rotation of the meter, and converting the signal to a digital pulse. To keep the system wireless, this prototype was designed with solar power compatibility to avoid the need for replacement batteries. A capacitor is used to power the meter overnight or in times of darkness. A small hydropower generator could also be designed for the system to achieve its need for small amounts of electricity.

Electricity Metering. The analog-to-digital conversion was designed to fit a Sangamo kilowatt-hour (kWh) meter by attaching a hall effect sensor to the first gear in the gear train that spins the needles and tracks the energy usage. The electronics from the

AWARE@home box were mounted inside the metal box that houses the meter as shown in Figure 5. The hall effect sensor sends a signal each time the customer uses 1/10 of a kWh, which is the highest resolution achievable using the meter. The magnet is mounted on the gear, away from the rest of the gear train, and the hall effect sensor is mounted to the base of the meter relative to the magnet's path of travel (rotation). An antenna was integrated into the meter enclosure with care taken to ensure that it is sealed properly such that water does not leak inside and damage the meter since the meter will be located outside the home. The system was designed to accommodate a small backup battery that can remember the current reading after a power outage. The system will notify the user when 90% of the battery life-expectancy has been reached, or if there the battery discharges completely. This is expected to be a rare event, as the battery can be designed to be rechargeable in the electricity monitoring system.

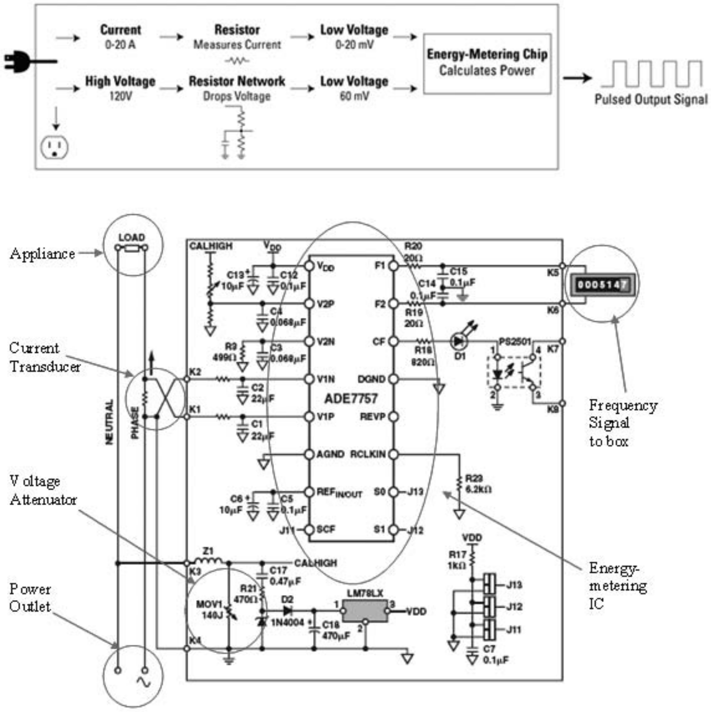
Gas Metering. The analog-to-digital conversion was designed to fit an Actaris Metris 250, which represents a common household gas meter based on the use of a diaphragm sensor. The meter measures the displacement of gas coming in and out of the diaphragm, which drives linkages underneath the gas meter. These linkages drive the first in a series of dials that record the volume of gas flowing through the meter. The dials are connected in series to record and display the amount of gas that has passed through the meter. A magnet was connected to the drive shaft with the aid of a lightweight, plastic diameter extender. The mass of this piece is insignificant compared to the drive shaft and resultant forces coming from the linkage. A hall sensor was then placed on a plastic molded fixture in line with the drive shaft at the bottom of the magnet's rotation. As the magnet rotates and thus changes flux, the hall-effect sensor creates a voltage signal as shown in Figure 6.

Appliance Monitoring. A separate wireless device was designed to supply the homeowner with consumption information from appliances receiving electricity from household power outlets (e.g. refrigerators, televisions, lamps, etc). The device is targeted for advanced users interested in better understanding the breakdown of electricity consumption by power outlets in their home. For instance, individual appliance electricity consumption information would help homeowners decide when it is time to replace a refrigerator or upgrade the light bulbs in their home to compact fluorescents.

Several designs were considered including a device between a power outlet and an appliance cord, a device attached to a circuit breaker, and a device clamped onto an appliance cord. Ultimately a device between a power outlet and appliance cord was determined to be the easiest and most useful concept for typical consumers. The design is based on the concept of a plug-in device where electricity used by the appliance runs through it and is measured and interpreted before wireless transmission to the homeowner's computer using a compact version of the AWARE@home signal processing and communication board. The monitoring device is plugged into the power outlet and the familiar 3-prong receptacle is where the appliance plugs in. The monitoring device then sends a wireless signal to the homeowner's computer. The working prototype was built off of an energy monitoring integrated circuit commercially available by Analog Devices (ADE7757), and inserted directly into the box shown in Figure 8. A high level block diagram and more detailed schematic for the wireless appliance electricity consumption monitoring unit are provided in Figure 8.

Software Interface. A complete software package has been developed that allows a user to interact with the AWARE@home system at progressively more detailed levels of information. The installation process is automatically run from an AWARE@home software CD or from a downloadable executable file. The baseline interface is designed for simplicity. For example, a "task bar tray icon" is available for users to click on at any time from the computer's operating system desktop. The icon is colored red when current usage rates are on course to greatly exceed the target monthly utility cost, yellow when likely to exceed the target, and green when unlikely to exceed the target. The red icon can be clicked for the user to access information regarding from which utilities the costs are coming with recommendations for taking action. Along with cost targets, environmental targets can be established for those interested. More advanced reports can also be readily generated at the click of a

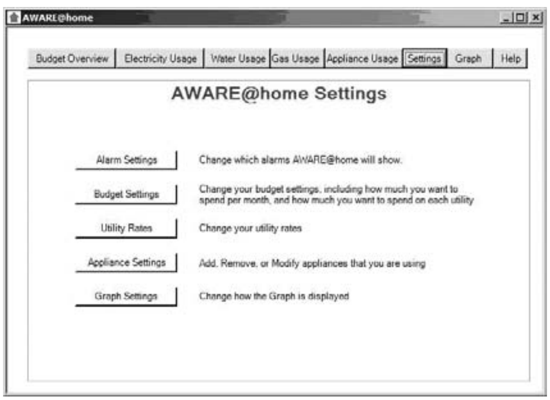
FIGURE 8. (Top) High level functionality of wireless electricity meter. (Bottom) Schematic of electricity metering implementation based on Analog Instruments ADE7757.



button as shown in Figure 9. The following paragraphs describe menu options available in the AWARE@home software:

The Settings Tab provides basic and advanced setup modes selectable by the user. Figure 9 shows the user interface for the advanced settings mode where the user can input the utility rates, the budget that he or she would like to keep for each individual utility, and the alarms he or she would like to make active. The basic settings screen only asks the user to input his or her utility rates and overall budget target. If the basic mode is activated, the user does not select alarm parameters, and only receives a prompt if the total financial budget is likely to be exceeded during the billing cycle.

FIGURE 9. The settings window from which a homeowner can select the features they would like to activate in the AWARE@home system.



The General Tab (Advanced Mode) is the central window in the AWARE@home interface where the user can monitor his or her utility consumption in several easy-to-read graphical forms. Pie charts at the top of the window indicate the percentage of the budget for each utility a homeowner has consumed at any given time in a billing cycle. The bottom of the window displays consumption in a line graph format where the user can specify the time period (weeks, months) that he or she would like to see plotted. The user can select which utilities to see plotted. For the individual utilities and total utilities cost, the program also shows the user a projected total usage rate based on the available consumption pattern information. This projection is intended to motivate the user to make spending decisions *before* the billing cycle is over. It is also the basis for sending user alarms regarding consumption. If the advanced window is not selected, the projection algorithm is still used, but it only notifies the user when total utility cost targets are likely to be exceeded.

The advanced mode also contains a button called "Update", which is used to refresh the information displayed by the software interface. Although the software refreshes each time the program is opened, a refresh button of this type is useful if the homeowner would like to test different appliances to identify the most energy efficient. A "Reset" button is also available to permit the appliance meter to be "zeroed out" when different appliances are plugged in to the AWARE@home system.

The Warning Pop-up appears on the screen with an appropriate message for the utility that is approaching the projected target cost the user has entered. The homeowner has the choice to plot the usage, to close the window, to be reminded later, or to ignore the warning and change the target usage.

Individual Appliance Window can be activated in advanced mode when a user would like to see how individual appliances are consuming electricity. Figure 10 displays the appliance electricity consumption window.

Pilot Scale Testing. The AWARE@home system was installed at the home of University of Michigan Associate Professor Steven J. Skerlos (Ann Arbor, MI) in December 2005 to measure electricity consumption. To date the system has performed as designed for eight months without the need for maintenance. As shown in Figure 11, two meters were installed in parallel, one with AWARE@home capabilities and one unmodified. The comparison revealed no significant difference in run speed, which was important to assure due to the concern that the hall effect sensors would noticeably slow the meter dials and reduce revenue for the electricity provider.

As seen in Figure 11, the system components were placed in a separate National Electrical Manufacturers Association (NEMA) enclosure due to the bulk associated with using prototyping components. In commercial implementation, all components could be inserted within the excess space found in existing meters. Figure 12 illustrates electricity consumption as displayed to the user from the electricity provider. The data from the test home's AWARE@home system is both displayed directly on the screen for the user, and is also transmitted via the Internet to the electricity provider to eliminate the company's need for meter reading. Periodic checks indicated that the data displayed by the electricity provider over the Internet is identical to the data published directly to the consumer by the system. The AWARE@home system also accurately predicted and measured electricity costs as provided in the normal monthly bill by the electricity provider.

Figure 13 illustrates electricity consumption data for the test home in February 2006 (full month) and for July 2006 (about 3 weeks), each with daily consumption illustrated in dollar increments. The re-

FIGURE 10. Individual Appliance Window.

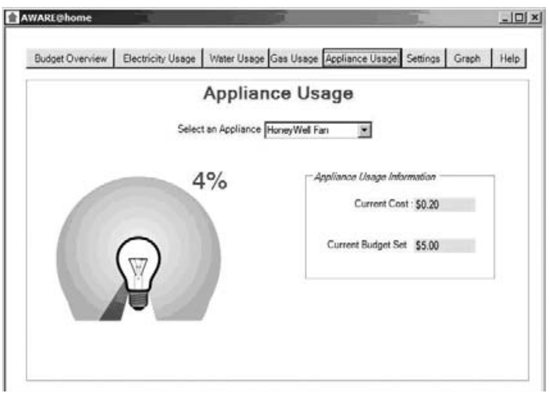
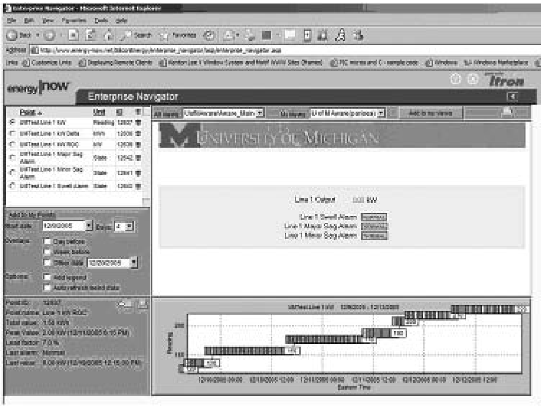


FIGURE 11. (Left) Meters running side-by-side to assure that AWARE@home system does not cause meter to "run slow". (Right) Prototype manifestation of AWARE@home system using off-the-shelf components as installed at the test home.

FIGURE 12. Data as received by electricity provider and securely published by the provider for the AWARE@home test customer to view via the Internet. Data published by the provider matches the data provided directly from the AWARE@home to the consumer.



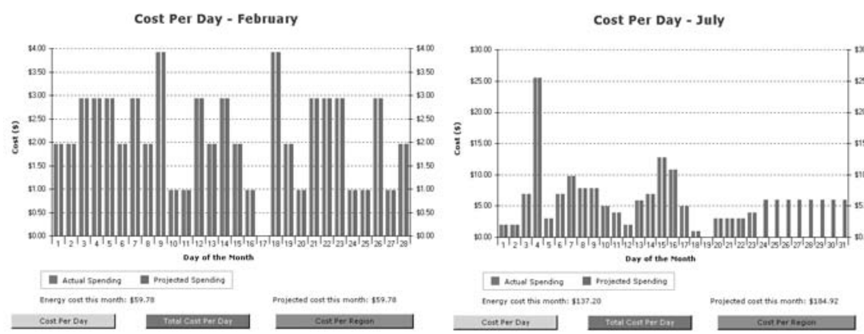
duced electricity costs associated with the winter months are evident in the data, as the home is heated using natural gas. The electricity costs in February are almost entirely derived from the fan used to force heated air through the home. Generally, expensive days in February are associated with larger amounts of heating, and more activation of the house fan. Days of zero consumption (actually, rounded to zero) were days the thermostat was set very low due to household vacancy. Generally the electrical appliances in the house use less than a dollar per day of consumption.

July data (shown through the 23rd) in Figure 13 show much higher electricity consumption due to air conditioning. Dates between July 23 and the end of the month are forecasted as a simple average of consumption for the previous days of the month. As suggested by the data, the 4th of July was a warm day where the air conditioning was set relatively low (72 degrees) and run all day long. Most days are set to 77 degrees, with a timer to inactivate the air conditioning while the occupants are out of the home. Most days do not dip below $3 per day and this is due to the house fan which is generally run constantly to filter allergens found in the air (e.g., pollen and soot). Days of cost less than $1 can be observed and these are generally associated with travel and deactivation of the air conditioner and house fan. The strong seasonal effect on electricity consumption observed during the pilot phase suggests that the AWARE@home software could be enhanced to make efficiency recommendations that are season specific. Such a feature would ensure that homeowners are notified most often when the potential gains in efficiency are highest and avoid false alarms when consumption excesses relative to targets are due to the weather rather than changes in homeowner behavior.

CONCLUSIONS

This paper described a simple-to-use and inexpensive technology called AWARE@home that was designed for households to receive information regarding their water, gas, and electricity consumption patterns with minimal effort through "at-home" wireless networks

FIGURE 13. (Left) Month of February 2006 electricity consumption and (Right) month of July 2006 electricity consumption measured in dollars for the test home. The test home is located in Ann Arbor Michigan. Significant const differences for electricity are observed for the test home between winter months and summer months.



(i.e., using 802.11 wireless communication protocols). The system also facilitates consumer access to conservation information. Functioning prototypes of the AWARE@home hardware and software were developed and validated. During the course of the project, the authors utilized numerous criteria to evaluate the success of the project including: technical considerations (e.g., does the technology work?), economic considerations (e.g., does the technology cost too much? is the installation of the technology possible with minimum economic impact on utility companies?), and societal considerations (e.g., is the technology easy to use? will people convert the information provided by the technology into tangible energy savings?). These criteria are discussed in the following paragraphs:

Does the technology work?

Yes. The digital water, gas, and electricity metering technology are as reliable as unmodified analog meters. The hall effect sensors with which the analog-to-digital signal conversion takes place were tested on gas, water, and electricity meters and the signals were transmitted wirelessly to a laptop computer. Custom built software receives the data, processes it, and presents it to the user at a basic level of information (e.g., cost alarms only) or at an advanced level of information (e.g., plots of electricity consumption for individual appliances). The technological obstacles have been overcome and the product is ready for marketing prototypes and commercialization.

Does the technology cost too much?

No. A "one-off" replicate prototype of the system using off-the-shelf component would cost less than $500 to produce. If the system were designed for production at marketing volumes, the cost would likely drop by a factor of 10. This is not only due to size and scale efficiencies, but also because the prototype has much more processing power, memory, and debugging capabilities than a final product would require. Based on the work to date the authors anticipate that the final manufacturing cost of an AWARE@home system will be $50-100. This price could go down depending on the volumes that are introduced to the market and the demand.

Is the installation of the technology possible with minimum economic impact on utilities?

Yes. Utilities are making the move toward radio enabled metering technologies to cut down on personnel costs. The incremental cost increases would be minimal (i.e., less than $10). The longer term impact on utility companies as homeowners reduce utility consumption is an area for future investigation. To the extent that conservation reduces the need for new power plants, a positive economic driver may exist for utility companies. To the extent that conservation increases existing over-capacity, a negative economic driver may exist for utility companies.

Is the technology easy to use?

Yes. Given that the meters will be installed by professionals, using an infrastructure for installation that already exists, the technology will be transparent to the utility companies. From the homeowner perspective, the software interface allows the user to select their desired level of information and alerting, thus custom fitting the interaction between the technology and the user. Future work will further focus on the people-oriented design of the user interface.

The original goal for the AWARE@home concept was for it to contribute to an average 1% reduction in the utility consumption of American households. Such a reduction would represent a significant start towards achieving the Nation's energy independence, as well as lead to cleaner air and water. It would also begin a paradigm shift that would help lead to further reductions in natural resource consumption and energy dependence in the future. The work reported in this paper overcomes a number of technological and practical barriers to this vision and in turn raises issues that must be addressed culturally and economically.

ACKNOWLEDGMENTS

The authors would like to begin by thanking the engineering students that worked on this project: William Ross Morrow, Jeremy Michalek, Erin MacDonald Kristine Auwers, Azwan Ashari, Amy Kopin, Clark Jansen, Michael Kulkarni, James H Norman, Bryce Carter, Tenisha Austin. We are also grateful to a number of students from the Steven M. Ross School of Business including Julie Bazinet, Greg Ezell, Gitesh Dubal, Wendy King, Suman Shankar, Jeff Wu who were also involved in the project. Two professors, Kim F. Hayes and Fred Fienberg, from the Department of Civil and Environmental Engineering and the Steven M. Ross School of Business respectively provided additional support to the proj-

ect. This project was made possible by the financial support of the Environmental Protection Agency People Prosperity and the Planet (P3) design competition. The views expressed in this paper are the views of the authors and do not necessarily reflect the views of the agency.

REFERENCES

1. AMDS (2006). http://www.amdswireless.com/index.htm.
2. Bishop, P. L. (1999). Pollution Prevention: Fundamentals and Practice. Boston: McGraw-Hill.
3. Black, J. S., P. C. Stern, et al. (1985). "Personal and contextual influences on household energy adaptations." Journal of Applied Psychology 70: 3-21.
4. Blueair (2006). Company Web Site (http://www.blueair.com/company/release_08.html).
5. CEC (2006). New Thermostat, New Temperature Node and New Meter. http://www.citris-uc.org/research/projects/new_thermostat_new_temperature_node_and_new_meter_cec.
6. Dulleck, U. and S. Kaufmann (2004). "Do customer information programs reduce household electricity demand?-the Irish program." Energy Policy 32(8): 1025-32.
7. EIA, Energy Information Administration. (1999). Energy in Africa, Department of Energy.
8. EIA, Energy Information Administration. (2000). Annual Energy Review 1998, U.S. Department of Energy.
9. EIA, Energy Information Administration. (2004). Emissions of Greenhouse Gases in the United States 1995, Department of Energy.
10. EPA, U. S. (2004). Energy Star: Consumer Electronics Holiday Promotion Sales Associate Training.
11. Gardner, G. T. and P. C. Stern (1996). Environmental Problems and Human Behavior, Allyn and Bacon.
12. NGSA, N. G. S. A. (2005). http://www.ngsa.org.
13. Schipper, L. (1996). "Life-Styles and the Environment: The Case of Energy." Daedalus 125.
14. SmartHouse (2006). Duke Smart House Web Page. http://delta.pratt.duke.edu/projects/efficiency.php.
15. WattsUp?, W. U. P. A. (2006).
16. WRI, World Resources Institute. (1990). World Resources, Oxford University Press.