



# Eco-Feedback on the Go: Motivating Energy Awareness

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**The EnergyLife mobile interface incorporates lessons from environmental psychology and feedback intervention to relay information from appliance sensors, offering a gaming environment that rewards users for decreased electricity consumption.**

**E**nergy saving has been a focus of human-computer interaction (HCI) applications for several years, and interfaces to promote user awareness of energy consumption are appearing on a variety of mobile devices. Commercial off-the-shelf energy-awareness products are now available as well as widgets and meters that promise to support the effective monitoring of household electricity consumption.<sup>1,2</sup> Both commercial products and research prototypes aim to surpass traditional monthly energy bills in providing feedback on consumption through a convenient medium, such as a cell phone or PDA.

As Figure 1 shows, these ecological-feedback technologies offer a range of information and opportunities to encourage rethinking energy consumption. Feedback, typically by device or use category, can include everything from information about instantaneous or historical household consumption to quizzes and tips. Media include desktop displays, mobile devices, or ambient interfaces, which address the periphery of users' attention by embedding information into surrounding objects.<sup>1</sup> An ambient interface could be a refrigerator door that changes color

to convey information about an ideal inside temperature, for example.

Although many interfaces provide feedback, we see a distinct lack of attention to lessons from environmental psychology and feedback intervention, such as avoiding monetary measurements and connecting feedback to a savings target like "use 5 percent less energy per year."<sup>2,3</sup> To address design principles based on those ideas, we created EnergyLife, an application for mobile devices that presents information about household electricity consumption for appliances, heating, illumination, and other kinds of electricity consumers in the typical household—information that each device with an energy-aware interface now provides separately.

Our aim is to provide a synergy of actionable feedback without overwhelming the user with information as well as to entice the user to check progress in saving electricity. To meet the second goal, EnergyLife incorporates a gaming environment that rewards users with new features as they achieve certain goals.

In a study of households that used EnergyLife, electricity consumption decreased 5 percent over the previous year's figures (without EnergyLife) during the study's last month. Although EnergyLife is a research prototype, we believe it represents a solid step toward making the average user aware of household consumption and of the actions necessary to reduce that level. Collectively, these reductions could represent a significant decrease in overall electricity use and lead to similar models for other energy types. We are currently conducting another study to refine our results.

|                | Consumption |         | Granularity |           | Medium |        | Advanced features |                  |           |
|----------------|-------------|---------|-------------|-----------|--------|--------|-------------------|------------------|-----------|
|                | Instant     | History | Device      | Household | Web/PC | Mobile | Ambient           | Tips and quizzes | Community |
| EnergyLife     | *           | *       | *           | *         | *      | *      | *                 | *                | *         |
| 7000 Oaks      | *           |         |             | *         |        |        | *                 |                  |           |
| UbiGreen       | *           |         |             | *         |        | *      |                   |                  | *         |
| Powe Explorer  | *           |         |             | *         |        | *      |                   |                  | *         |
| Efergy         | *           | *       |             | *         | *      |        | *                 |                  |           |
| Navetes        | *           | *       | *           | *         | *      | *      | *                 |                  |           |
| Agilewaves     | *           | *       | *           | *         | *      |        |                   | *                |           |
| Onzo           | *           | *       | *           | *         | *      |        | *                 |                  | *         |
| Cent-A-Meter   | *           |         |             | *         |        |        | *                 |                  |           |
| Microsoft Hohm |             | *       | *           | *         | *      |        |                   | *                | *         |
| Tendril        | *           | *       |             | *         | *      | *      |                   | *                | *         |
| Energy Joule   | *           |         |             | *         |        |        | *                 |                  |           |
| EnergyHub      | *           | *       | *           |           |        |        | *                 |                  |           |
| Wattson        | *           | *       | *           |           | *      |        | *                 |                  |           |
| Owl meter      | *           |         | *           |           | *      |        | *                 |                  |           |
| Energy Meter   | *           |         | *           |           | *      |        | *                 |                  |           |
| Ewgeco         | *           | *       |             | *         |        |        | *                 |                  |           |
| Google Pow     | *           | *       |             | *         | *      |        |                   |                  |           |
| Greenbox       | *           | *       |             | *         | *      |        |                   |                  |           |
| Manodo         | *           | *       | *           |           | *      | *      | *                 |                  |           |

**Figure 1. Features in current eco-feedback technologies. Both research prototypes (light orange) and commercial solutions (dark orange) aim to make users more aware of household energy consumption.**

### ELEMENTS OF AN ECOLOGICAL FEEDBACK SYSTEM

As Figure 2 shows, EnergyLife is layered atop our BeAware framework,<sup>1</sup> which takes data from a dedicated sensor on the household's fuse box as well as from wireless sensors in appliance plugs. In this way, the framework can measure electricity consumption both from the household overall and from individual appliances. The framework accommodates either off-the-shelf sensors such as Plugwise or wireless sensors that we designed to offer more precision and better connection. At present, BeAware processes data from eight sensors—refrigerator, television, washing machine, microwave, computer, and three generic sensors. The framework could easily accommodate more appliances, but we chose these five because they are common to the users in our evaluation study. The three generic sensors offer additional placement choices, such as coffee machines, stereos, and electric heaters.

Within the BeAware sensing layer is the BeAware base station (not explicitly shown), which processes all household data. It handles communication to all sensors and ambient interfaces, acts as an Internet gateway, and supports both BeAware's 433-MHz wireless network and commercial ZigBee-based networks. The framework's

Internet services communicate with the user interfaces directly or through the base station to two embedded ambient interfaces: the light ambient interface (LAIT) and Watt-lite Twist, a flashlight-shaped tabletop projector.

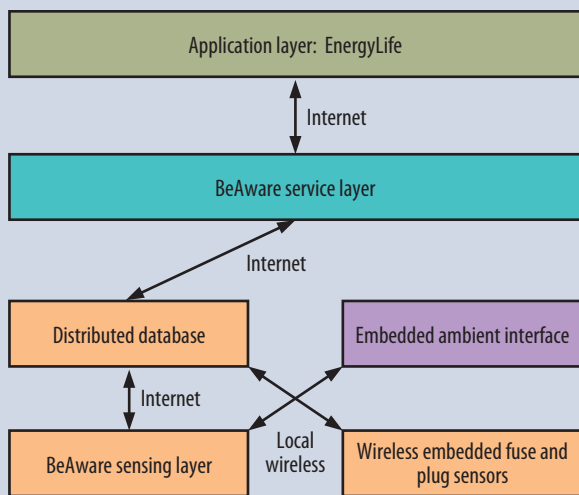
Together these components make up the BeAware framework: the sensors and BeAware base station form the system, which feeds data to the EnergyLife mobile application and to the LAIT desktop and Watt-Lite projector interfaces.

### Domain definitions

In our work, *energy* is essentially electric power, although we recognize that a household can use other energy types, according to region and building. A *household* is the smallest organic energy system in a residential sector that purchases electrical devices, monitors their use, and pays the bills to use them. An *electrical device* consumes electricity; it includes both home appliances and other consumption sources such as lights.

Within the household are *users*, who have various roles that involve the use of electrical devices.

*Consumption* and *conservation* are the two facets of energy awareness that acquire meaning through a reference point to discriminate them, such as a consumption



**Figure 2.** The BeAware framework. EnergyLife is one of several layers within the BeAware framework. Sensors connected to appliances through the BeAware base station (part of the BeAware sensing layer) feed data to ambient interfaces and a database, which in turn feed data to a service layer. EnergyLife uses this data to provide user feedback through EnergyLife. Ambient interfaces use the data to organize abstractions such as consumption pie graphs.

level. In our case, the reference point is a household's weekly consumption. The *baseline* reference point is the average electricity consumption during the calendar week prior to the current day. The baseline also helps highlight any significant consumption difference relative to the previous week about which the user might be unaware. Knowing that difference can help all household members plan for next week's consumption to compensate for excesses in the current week.

*Feedback* is information about the consequences of household actions that involve electricity consumption. Two basic types of feedback are consumption/saving information and smart advice tips.

Finally, *awareness* is the knowledge that users acquire about how and why to reduce waste by operating devices more efficiently, including hints that show a larger environmental impact. Awareness is a condition for conservation, so awareness tools are a necessary counterpart to feedback provision. EnergyLife provides this awareness by offering tips and quizzes.

### Feedback and system requirements

Researchers from the behavioral sciences have studied how to provide feedback to persuade users to change behavior,<sup>3,4</sup> studying how feedback relates to behavior and the best format for providing feedback. Studies have found, for example, that it is easier to persuade users by addressing specific rather than general behaviors,

since each behavior has its own reasons and constraints. Similarly, effective feedback should be actionable, demonstrating a way to fill the gap between current and desired actions. Thus, system designers should tailor feedback to the users' specific behaviors and profile. The goal must be constantly clear to the user, be tailored to the specific household, and provide instructions for how to achieve the goal.

Too much information might lead to overload and drop-outs,<sup>3</sup> so the displayed information should be self-explanatory; the best strategy is to have the interface present information in successive detail levels, not all at once.

Feedback format is also a critical design principle. Studies show that financial savings is not a long-term motivator relative to behavioral efficiency measures. Thus, designers should opt for historical feedback—insights that compare current and past distance to the goal—over feedback that compares a user's achievements with those of others. Because each household has its own constraints, such a comparison risks being irrelevant, flattering, or frustrating.

Other feedback and system requirements include

- *Nonintrusiveness.* The system should not disrupt everyday family habits by requiring additional measures and should not require substantial deviation from the user's intended activity.
- *Intuitiveness.* System interaction should encourage the correct user input without requiring a manual.
- *Energy efficiency.* The feedback system itself should be energy-efficient.
- *Privacy.* Devices that personalize feedback should address the possible risks to privacy and protect the user against them.
- *Sustained involvement.* The interface should evolve and reward improvements to keep the user enticed and motivated after curiosity about the system wanes.

### Design principles

On the basis of these requirements, we evolved four main design principles for EnergyLife and the two ambient interfaces. The first was to provide near-real-time feedback of electricity consumption related to a reference point—the baseline overview of past consumption behavior. This comparison influences or informs the user's choice of future consumption behaviors. In addition, EnergyLife measures consumption in watts to show the effects of small behaviors, such as keeping a device on standby, and gives the cost of energy consumption to the environment when these behaviors accumulate, such as telling the user how many trees must absorb the carbon dioxide that an appliance has released. Awareness tools such as tips and quizzes related to the monitored devices direct users' efforts by reminding them of desirable conservation practices.

Another design principle recognizes the need to support engagement for sustained interaction and social incentives. To this end, we structured the EnergyLife game in several levels, offering players challenges and opportunities for knowledge building. Our aim was to allow long-term engagement with the application and to have users learn its features gradually. EnergyLife accomplishes this aim through game levels.

The third design principle was to ensure the interface's usability through intuitive and coherent navigation metaphors. In the mobile applications, we incorporated this principle through touch-screen technology using a card carousel that anchors the other interface elements. The ambient interface promotes usability by embedding consumption information into daily routines through familiar objects. For example, when a household member turns on the lights, they might dim slightly to indicate an increase in overall household electricity consumption.

Finally, EnergyLife acknowledges the actors responsible for electrical conservation in the household and relates them within the larger household nucleus. EnergyLife supports competition, discussion, and reflection inside the household by interlacing individual and family achievements and providing community tools. In this way, it aims to facilitate a shared process of awareness building by considering electricity consumption from a social viewpoint. If feedback follows requirements, such as being actionable, intuitive, tailored, and nonintrusive, users should be able to easily absorb the game into their daily life and routines.

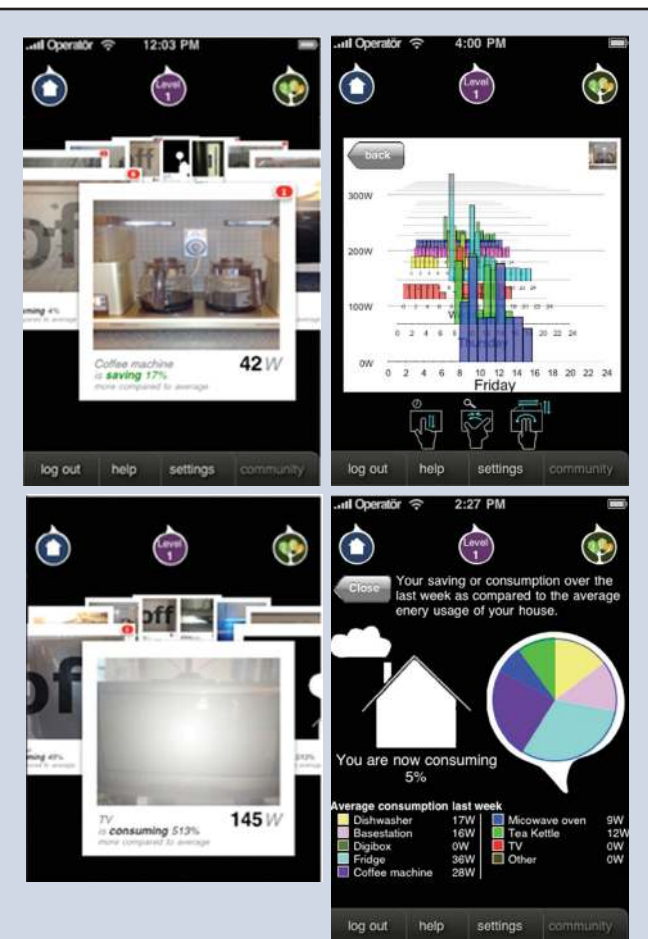
## COMMUNICATING CONSUMPTION

Persuasive eco-technology games like Eco Island<sup>5</sup> and PowerAgent<sup>6</sup> rely on self-reporting or aggregate measures and focus on competition among households. EnergyLife differs from these games in two ways. First, we customized the application<sup>7</sup> by acknowledging the household as the target and identifying the smaller, related units in which it is articulated. Second, EnergyLife uses real consumption data and feeds it automatically into the system, offering timely feedback that reflects any nuance of changed behavior.

### Appliance cards

Figure 3 shows the EnergyLife mobile interface, which consists of a touch screen displaying a 3D card carousel. Each of eight cards represents an electrical appliance that a sensor is monitoring, and a household card shows overall consumption. Each appliance card shows that appliance's percentage consumption or savings relative to its average. Users can "flip" a card to see additional information and functionality for that appliance.

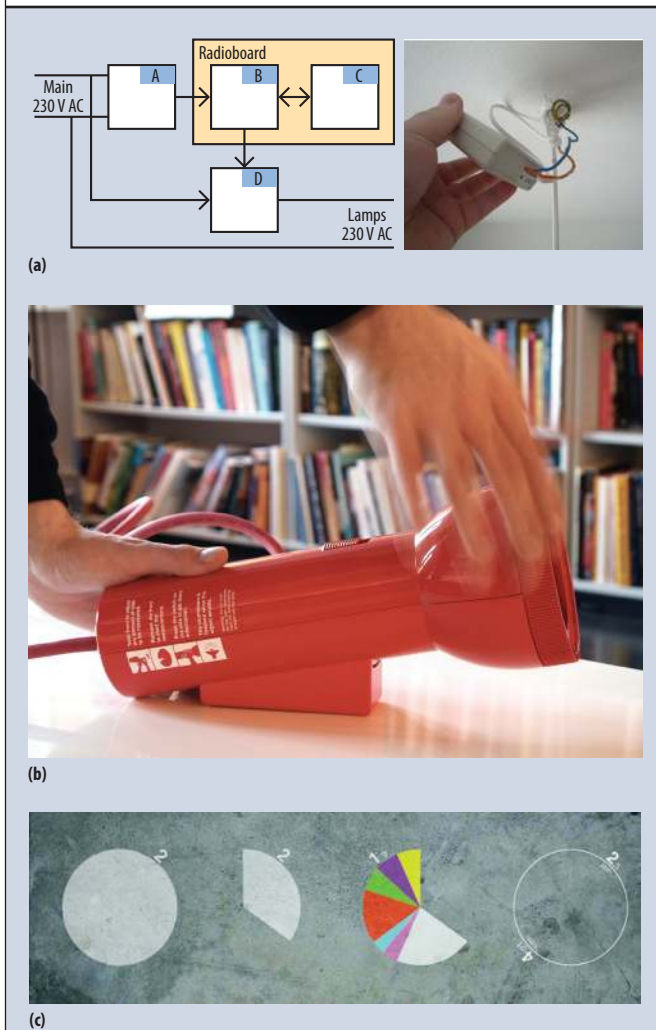
The front of the card displays a picture of the appliance, its current electricity consumption, and how much electricity the appliance is saving. The menu on the back of each



**Figure 3.** EnergyLife interface views. The main interface is EnergyLife's card carousel (upper left), which provides consumption history (upper right) and signals overconsumption through blinking cards (lower left). Users can also see a consumption breakdown per device. At present, eight sensor cards are available, each representing an electrical appliance; along with a ninth card (lower right) that reflects the household average on the basis of data from the dedicated sensor in the fuse box. The "average" in the card text refers to the average for that appliance. The small red dots on the upper right corner of some of the cards indicates that the user can read advice or take a quiz.

card lets users access advice, a quiz, or consumption history for that device. A household card shows consumption for the entire household. Users also see consumption history in the form of graphs (top right in Figure 3). Each row represents one day, and each column represents consumption for one hour. Users can browse the previous day's data using multitouch interaction with the graph itself.

To help the user conserve energy and gain awareness, the application provides advice tips and quizzes at certain times. Random advice appears once daily, taken from a tips repository. Smart advice is triggered by a condition connected to wasteful behavior, such as a television being



**Figure 4. Ambient interfaces.** (a) The light ambient interface (LAIT) microcontroller circuit, shown as a diagram and completed controller, interfaces with an installed light and feeds information to the BeAware base station via Bluetooth. (b) The Watt-lite Twist resembles a large flashlight that the user can twist to the desired kilowatt-hours of consumption. (c) During the measurement period, the flashlight projects consumption progress, starting at the left with a white circle (the target amount of kilowatt-hours) or, which disappears as energy is consumed, indicating consumption breakdown by device. When the target amount of kilowatt-hours has been consumed, the white circle disappears, leaving a darkened shadow of a circle instead.

on for days. The implication is that someone forgot to turn it off and it has been running while no one is watching.

In advanced levels, advice tips are triggered for specific situations and give tailored feedback, such as “28 trees had to absorb the carbon dioxide your PC produced this week. Try to reduce its use by turning it off when you don’t use it.” The calculation of 28 trees stems from the exact number of kW consumed during the week by the monitored desk-

top PC and is triggered after this consumption exceeds a certain value.

### Earning awareness points

EnergyLife users progress through game levels by earning awareness points. At Level 0, the application only processes measurements from the sensors to calculate the starting baseline. From the next level, users must acquire a certain number of awareness points, either by saving electricity for a specified time, reading advice, or correctly answering quiz questions. At subsequent levels, EnergyLife provides context-aware advice tailored to use parameters for that appliance, and unlocks a game community in which users can interact with EnergyLife users from other households and gain points for each message to improve their position with respect to the other players.

Unlike a direct competition between households, our approach uses gaming behavior to motivate individual change. Competition is to gain points in a game, not explicitly to save utility cost, although that is certainly a by-product.

### Ambient interface components

The EnergyLife game includes specific goals and detailed feedback that require a reasonable amount of user effort and voluntary interaction. Two ambient interface components complement the game by sending messages to and receiving information from the BeAware base station, which they use to control consumption. Their aim is to alert users of consumption states, particularly overconsumption, and to indicate when it would be beneficial to look at the mobile application. Relative to the card carousel, which users voluntarily select, the components provide constant representations of electrical consumption and savings in a more abstract form.

**Light ambient interface.** Figure 4a shows the LAIT controller, which controls fixed household lighting and lamps to cue the user about the state of electricity consumption. The BeAware base station monitors incoming messages and requests from the LAIT service layer, and controls individual lamps in the household. A small printed-circuit board transformer and a low-power regulator power the LAIT.

If the household is on target, the lamp will turn on as it usually does. If the household is off target, the light will slowly brighten, from dark to full illumination.

**Watt-lite Twist.** As Figure 4b shows, the Watt-lite Twist is essentially an oversized flashlight that projects household electricity consumption as a pie chart during a specified number of kilowatt-hours, as Figure 4c shows.

We wanted Watt-lite Twist to provide a more intuitive representation than LAIT because studies show many people do not fundamentally grasp concepts used in

communicating energy. For example, an interview of 14 households transitioning to smart meters revealed only a vague understanding of a smart meter's specific functions. Indeed, none of those interviewed understood the concept of kilowatt-hour except as "something I pay for."<sup>8</sup>

Results from another study, this one of households using the Energy Aware Clock, also showed a failure to grasp the multifaceted concept of a kilowatt-hour.<sup>9</sup> One participant understood that appliance type affects the kilowatt-hours consumed, but she did not realize that a consumption calculation had to include the time and frequency of use.

With those studies in mind, we designed Watt-lite Twist to make it easier to understand the kilowatt-hour concept and how it relates to the electricity consumed in various activities using household appliances.

At the heart of the Watt-lite Twist is the Dingoo, a handheld game console modified with a Linux OpenWRT solution. A miniature laser projector attaches to the Dingoo, which responds to the movement of the front of Watt-lite Twist and starts the projection. Watt-lite Twist communicates with the BeAware base stations via Bluetooth. The station in turn communicates with the appliance sensors so that it can feed the Dingoo information about the electricity that individual appliances are consuming.

Starting Watt-lite Twist by winding its front part to a specific kilowatt-hour or fraction thereof gives users a feel for the duration of a kilowatt-hour—somewhat like starting an egg timer. Users can choose to twist the dial to anywhere from the minimum 0.1 kilowatt-hour to the maximum of 2 kilowatt-hours.

As the progression in Figure 4c shows, the first picture projected after the wind-up is a white circle. A black slice enlarges the allotted time. By sliding a switch at the top of Watt-lite Twist, the user can project a color pie chart showing the proportion of energy that each appliance is consuming, information that is based on communication with the BeAware base station. When the consumption of the target kilowatt-hour amount is complete, Watt-lite Twist issues an audio alert signal, and the projection shows a darkened circle with the time taken to achieve this target.

## REMAINING CHALLENGES

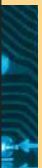
In creating the components of our BeAware framework, we identified several open issues related to designing energy awareness systems: pervasive sensing, the need for multiple modes of interaction, the potential of pattern tracking in a particular context, and the tradeoffs of combining platforms.

### Pervasive sensing

Integrating individual sources of information about household electricity consumption is a significant usability challenge. An effective monitoring system should provide

an overview by highlighting power-eaters and tracking consumption routines, yet remain intuitive to use. The range of device types in a single household can result in large amounts of information, which can be confusing and overwhelming to view. To mitigate this complexity, feedback must be as simple as possible, such as having device categories. The lights category, for example, could consolidate information only about individual lights in a household.

Measuring power consumption to conserve energy is a way to recognize user activities.<sup>10</sup> A system can measure power for the entire house,<sup>11,12</sup> or for selected sockets.<sup>13</sup> Substantial challenges remain in fingerprinting electrical devices—characterizing electrical attributes, detecting use, and recognizing any use patterns—and breaking down overall household consumption according to different categories or devices. A breakdown using only one sensor seems to be unrealistic for the moment, as does



**Substantial challenges remain in fingerprinting electrical devices and breaking down overall household consumption according to different categories or devices.**

the deployment of sensors for each electrical device. We chose a mixed approach for EnergyLife, using one sensor for the entire house to enable at least some fingerprinting for larger loads, as well as inserting sensors in key plugs for more targeted sensing.

Other challenges include choosing the best communication medium from current wireless options, such as ZigBee and low-power Bluetooth. Designers must carefully evaluate parameters such as reach, bandwidth, and scalability, since competing solutions remain despite federated efforts to propose standards.

### Multimodality

Household energy-awareness systems should not disrupt the inhabitants' everyday routines. Offering nonintrusive feedback that does not tax the user is an important design challenge in mobile energy-awareness applications because mobile device size continues to shrink while the amount of important energy-consumption information is increasing. This combination poses a temptation to overload the display.

Another challenge stems from the dynamics of mobile device use. A user can be in a variety of use scenarios, but in each case, vision is the primary sense used to accomplish a task. However, many of these scenarios impose no restrictions on also using other senses. For

example, a user searching the Web for a restaurant address can still hear an alarm to remember to turn off the coffee machine.

In energy awareness, multimodal interaction is a promising way to reduce display complexity. Devices like the iPhone have built-in vibration motors and audio speakers that can provide energy-awareness information without requiring the user to look at the device. Moreover, a simple vibration might use less energy than displaying the same information on the device's screen.

### Context awareness

Detailed energy sensing is an opportunity to track user activities. Additional information from other sensors (temperature, lights, mobile phone presence and use) can provide data to recognize events and situations and trigger different system responses. Building on this smart advice idea, systems can track household energy-use patterns by identifying use profiles and their effect on energy conservation.

Future work in context awareness should include developing catalogs, models, and classifications of meaningful situations along with recognition algorithms, taking into account that households differ significantly in their energy-use habits.

### Combined platforms

Ubiquitous computing allows system interaction through a variety of modalities and interaction platforms. Mobile devices and ambient (embedded) interfaces can provide energy-efficient user interaction. Smart phones are on most of the time, and placing sensors on installed lights doesn't require large amounts of additional energy. Rather, the main challenge is how to synchronize platform components. Ambient interfaces that require embedded computing pose additional challenges such as energy-efficient connectivity and scalability, for example.

Our ambient interface uses the same communication platform as the wireless sensors, and the latest sensor we developed uses the same component to track the use of lights and communicate the information to users. Our vision is that all devices, including power plugs, will have electricity sensors and the ability to communicate with each other.

**M**obile and embedded computing is already pervasive, so a logical next step is to exploit the technology for the betterment of society or the environment. EnergyLife harnesses the ubiquitous nature of mobile devices to address energy awareness by helping users understand how their energy-consumption habits contribute to or degrade environmental health. By providing a shared awareness of energy consumption, real-time

feedback, and a gaming environment that helps sustain interaction, EnergyLife overcomes many of the problems encountered in other energy-awareness system designs.

EnergyLife is not just a concept. We tested it several times before releasing the first prototype.<sup>3</sup> We then installed the working system in five research-team and eight lay-user households in northern and southern Europe, all of which completed a longitudinal three-month trial. A second trial with another 10 households is in progress, and we anticipate results by August 2011.

A preliminary analysis of data from the first working-system trial shows decreased consumption from the trial's start to end, and most participants agreed that they had changed their energy-consumption habits. Comparing consumption during the trial's last month with the same period in the previous year (which we inferred from energy bills) also shows a 5 percent decrease in overall household consumption.

Naturally, issues remain, such as pervasive sensing and user empowerment, as well as the multimodal integration of different displays with different feedback modalities. However, our preliminary studies with EnergyLife are encouraging. The benefits of creating mobile and embedded energy-awareness systems are countless, but, undeniably, the most important contribution is the shared awareness of how individual actions influence environmental health. **□**

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