

# USEM: A Ubiquitous Smart Energy Management System for Residential Homes

Masood Masoodian\*, Elisabeth André<sup>†</sup>, Michael Kugler<sup>†</sup>, Florian Reinhart<sup>†</sup>, Bill Rogers\*, and Kevin Schlieper<sup>†</sup>

\*Department of Computer Science

The University of Waikato

Hamilton, New Zealand

Email: {masood, coms0108}@waikato.ac.nz

<sup>†</sup>Human Centered Multimedia

Augsburg University

Augsburg, Germany

Email: andre@informatik.uni-augsburg.de,

{michael.kugler, florian.reinhart, kevin.schlieper}@student.uni-augsburg.de

**Abstract**—With the ever-increasing worldwide demand for energy, and the limited available energy resources, there is a growing need to reduce our energy consumption whenever possible. Therefore, over the past few decades a range of technologies have been proposed to assist consumers with reducing their energy use. Most of these have focused on decreasing energy consumption in the industry, transport, and services sectors. In more recent years, however, growing attention has been given to energy use in the residential sector, which accounts for nearly 30% of total energy consumption in the developed countries. Here we present one such system, which aims to assist residential users with monitoring their energy usage and provides mechanisms for setting up and controlling their home appliances to conserve energy. We also describe a user study we have conducted to evaluate the effectiveness of this system in supporting its users with a range of tools and visualizations developed for ubiquitous devices such as mobile phones and tablets. The findings of this study have shown the potential benefits of our system, and have identified areas of improvement that need to be addressed in the future.

**Keywords**—Building energy management, energy usage monitoring; energy usage visualization; information visualization; mobile user interfaces; user evaluation; persuasive technology.

## I. INTRODUCTION

People use energy not only for their basic everyday needs such as cooking, cleaning, warming or cooling their houses, transport, etc. but also to make their lives more comfortable and enjoyable. The worldwide energy consumption is therefore increasing rapidly as the world population grows, and more and more of us demand higher standards of living with better life styles.

However, as the worldwide energy resources are limited, and the available fossil-fuel as our primary source of energy is rapidly dwindling, we need to find alternative means of generating energy through renewable resources, as well as saving energy whenever possible. Since the 1970s, when the first oil crisis happened, many technologies have been proposed and

developed to assist consumers with saving energy by, for instance, using it more efficiently. In the past, most technologies have focused mainly on energy consumption by the industry, transport, and service sectors. In more recent years, however, increasing attention has been given to residential energy use.

Strategy adopted by existing systems for management and control of energy consumption in residential homes can be divided into two categories, automated and non-automated (manual). Automated systems use mechanisms for controlling home appliances, so that energy-wasting behavior by users can be partly mitigated (e.g., automatically turning off the heating when windows are left open). Non-automated approach to energy saving in private households, on the other hand, can be broken down into two main parts. First, the residents must identify saving potentials in their household, which requires them to be aware of the energy consumption of individual appliances. Second, once they know how and where energy is actually being used, they need to be assisted and persuaded to change their behavior to reduce their energy usage. Unfortunately, however, there are some challenges in achieving both of these two parts. In relation to the first part, usually people know their overall energy consumption (aggregated for the entire household), because that is what their energy providers bill them for. On the other hand, finding out how much energy each device actually uses or how much of the overall consumption each individual person in a house has consumed (i.e., disaggregated consumption data), is very difficult. As challenging as solving this essentially technical problem may be, overcoming the challenge of changing people's behavior to save energy while still living a comfortable life is even harder.

In this article, we expand on our research work presented at ENERGY 2014 conference [1], which introduced a system called Ubiquitous Smart Energy Management (USEM). This system not only provides an automated solution for reduction of electricity usage, but also caters for the non-automated approach by providing detailed energy consumption information to users, and incorporating various tools to assist and encourage them to change their energy consumption behavior.

We start this article with a review of existing building energy management systems, and related research, with a particular focus on residential homes (Section II). We then describe the design of our Ubiquitous Smart Energy Management system (Section III), its client applications (Section IV), and the current prototype (Section V). This is followed by discussion of a laboratory-based study we have conducted to evaluate the usability of the client applications of USEM (Section VI). Finally, we briefly provide the results of an analysis of the capabilities of USEM against existing guidelines for the design of persuasive technology (Section VII), and draw some conclusions (Section VIII).

## II. ENERGY MANAGEMENT IN RESIDENTIAL HOMES

There are many existing technologies that target saving energy in residential and commercial buildings. These systems are broadly categorized as Building Energy Management Systems (BEMS). They generally consist of two types of components: the physical hardware used to monitor and control energy consuming devices, and the software components that allow various levels of user interaction with the hardware.

The hardware components can further be categorised into either monitoring, or control hardware. Energy monitoring systems can be single-point or distributed. Single point systems usually provide aggregated consumption data for the entire building, while distributed systems are generally wireless, connect to each energy consuming device at the plug level, and therefore provide disaggregated energy usage data for the individual devices they are connected to. Examples of energy monitoring systems for the residential market include systems such Current Cost [2], the Energy Detective [3] and Wattson [4]. However, these systems only show users how much energy they have consumed in the past, and at best make some general suggestions about how to reduce energy usage in the future. Generally, these types of systems cannot actively control appliances to put energy saving tips into practice.

Control hardware, on the other hand, are mainly used by Building Automation Systems (BAS) to actively control energy consuming devices in a building, usually in combination with a range of sensors that react to their environment (e.g., an air-conditioning system can be automatically switched on/off based on temperature sensor data). Examples of such systems include HomeMatic [5], Gira [6], Intellihome [7], Z-Wave [8], and HomeKit [9].

It should however be noted that the distinction between monitoring and control hardware is gradually diminishing. For instance, the Wattson [4] monitoring system works with Optiplug [10] intelligent sockets to switch on/off devices connected to them depending on the availability of surplus electricity.

Kazmi et al. [11] provide an excellent review and comparison of hardware technology used by existing Building Energy Management Systems. They also discuss how BEMS aim to support users with monitoring their energy consumption, providing real-time feedback to them, and allowing users to automatically or manually control their energy consuming devices. Of particular interest here is the role of feedback in

encouraging and supporting residential households in reducing their energy consumption.

Although various studies have shown the importance of feedback in reducing energy consumption [12], [13], [14], [15], [16], there are not many systems to support domestic users with managing and visualizing their energy consumption details, and therefore, easily understandable and persuasive feedback systems are likely to appeal to domestic users [11]. There are however a range of issues that feedback systems need to take into account to make them successful, including those resulting from theoretical frameworks that define consumer behavior (e.g., goal-setting, feedback intervention, etc.) [17], [18], [19].

Based on such theoretical frameworks, Fischer [15] emphasizes that feedback should: be based on accurate consumption data, be provided frequently, involve interaction and choice for households, involve appliance-specific breakdown (i.e., disaggregated), be given over a longer period, involve historical or normative comparisons, be presented in an understandable and appealing way. Similarly, based on their review of intervention studies of residential energy conservation, Abrahamse et al. [12] identify the importance of feedback as an effective strategy for reducing energy consumption, particularly if it is given frequently, is combined with goal-setting, allows comparison, and is supported with rewards.

An important factor to take into account is the presentation of feedback, which is crucial in motivating and altering users' behavior to save energy [11]. In addition to conventional forms of feedback (e.g., in textual format, printed records, etc.), technology can be used to provide feedback in a number of other forms, including graphical visualizations, ambient devices, games and social media. These are briefly reviewed below (also see [20], [21], [22]).

### A. Graphical Visualizations

Graphical (statistical) visualizations are widely used for presentation of energy consumption data (for a review see [23]). Vine et al. [24] present a summary of the studies, which have investigated the visualization techniques that are used to present users with information on their energy consumption. They report that the most popular visualization techniques include pie and bar charts. However, the preference for one technique or the other seems to be both user- and context-specific, with different visualization having different effects on influencing users' behavior [25].

### B. Ambient Devices

Kim and colleagues [26] outline design requirements for ambient devices to create effective persuasion. In a study they identify ten stages from raising awareness to behavior change and the maintenance of behavioral changes. Based on their findings, they then propose several persuasion methods, including subtle indicators for ambient tracking and visually appealing rewards.

The Energy AWARE Clock [27] is an example of an ambient device that visualizes current and past energy usage of a

household. The three design principles of complexity, visibility and accessibility are used to reduce the complexity of consumption data, make visible “hidden” or “not directly obvious” electricity consuming devices, and have the consumption data easily accessible. A three month user study of nine households showed that the users developed a better awareness of their energy use, and thought about changing their behavior to save energy.

Other ambient devices have been developed to help users save other resources such as water. Examples of these include UpStream [28] and Shower Calendar [29]. Studies of these systems have shown that they lead to reduction in water consumption.

Ham and colleagues [30] conducted a study to see if ambient technology has the capability of persuading people subconsciously. In this study, the participants were asked to rate the energy usage of three devices. The three groups of participants either received supraliminal feedback (presentation of a smiling or sad face for 150 ms), subliminal feedback (presentation of a smiling or sad face for 25 ms) or no feedback at all on their given answers. The feedback was given in the form of smiley faces directly after rating the consumption of a device. The results indicated that both groups with feedback gave more correct answers on average than the group without any feedback. Furthermore, the subliminal feedback group gave comparable answers to the supraliminal feedback group, and they also stated that they had not consciously seen any feedback.

### C. Games and Social Media

Several systems have been developed to encourage people to conserve energy and increase their energy use awareness through games and social media. The Power Explorer [31] game tries to help teenagers save energy. This mobile phone game takes into account the changes in energy consumption at home by the players. There are different game elements: habitat, pile and duels. The habitat shows the user’s avatar in a virtual climate environment, in which energy usage causes CO<sub>2</sub> clouds to appear, which is bad for the avatar. In the pile view, players can see how they are ranked compared to other players, and in the duels players compete directly against each other. The goal of the duels is to increase the energy awareness about appliances, since players have to adjust their household energy consumption to win. A study of Power Explorer showed that a group of players consumed about 20% less energy than a reference group of non-players.

Other research has focused on integration of home energy feedback into social networks. For instance, Mankoff and colleagues [32] demonstrated integration of energy usage feedback to the MySpace social network to motivate people to conserve energy. Similarly, Foster and colleagues [33] have developed a Facebook application, and have shown in a study that energy consumption can be reduced through social encouragement and competition. Petkov and colleagues [34] expand the idea of social comparison with their social application EnergyWiz, in which users can compare their energy usage with their own history and that of others.

Midden and Ham [35], on the other hand, performed a laboratory-based experiment, in which participants could save energy while using a simulated washing machine. This study showed that social feedback provided by an embodied agent was more effective than just factual feedback about the energy savings made.

These types of social network related systems rely on surveillance and self-monitoring techniques. However, they generally only provide feedback at the household level and not at the individual user’s level.

### III. UBIQUITOUS SMART ENERGY MANAGEMENT

Based on the findings of the reviewed studies, and various recommendations made for designing effective feedback systems for supporting energy conservation in residential homes, as discussed in the previous section, we have iteratively designed and developed our Ubiquitous Smart Energy Management (USEM) system. The aim of this system has been to support the monitoring of energy consumption data, and utilizing this data to allow users to set realistic goals. USEM then attempts to encourage users to achieve these goals by providing them with accurate, real-time, and disaggregated feedback. USEM also aims to provide manual, as well as automatic, control of devices based on users’ choices, and to allow them to intervene in operation of the system based on the feedback they receive.

The design of USEM has followed a user-centred design approach. This started by developing a set of personas, and scenarios of use, which allowed us to then identify a set of user requirements for USEM. We used the following personas in our scenarios:

- **Frank** is 38 years old. He works as a clerk in a local car rental company. He has two children and is married to Franny. Frank drives an electric car.
- **Franny** is 35 years old. She used to be a receptionist, but is not working currently so that she could take care of her two children.
- **Max** is a 12-year-old boy. He usually goes to school from 8am to 1pm.
- **Fabienne** is a 5-year-old girl. She usually goes to kindergarten from 9am to 1pm.

Because of the two children, it is important for the family to maintain a comfortable temperature level in the house while the children are at home. They all get up at about the same time and they all need warm water to shower. They have solar panels installed on their roof, but they also rely on energy from the local energy provider in case the panels cannot generate enough energy for an autonomous power supply.

From several scenarios that we developed, we identified the following requirements for USEM, which include a combination of automated and non-automated strategies for energy usage management:

- **Controlling devices:** The system must be capable of controlling devices. For example, turning them on and off, or changing their operating mode.
- **Continuously active tasks:** USEM must support continuously active tasks, such as maintaining a certain room

- or water temperature, or recharging an electric car to a certain level.
- **One-time tasks:** One-time tasks run only once when initiated by the user, and have a defined end time. Such tasks include, for examples, washing the laundry, or pre-heating the oven.
  - **Task scheduling:** The system has to provide a mechanism for intelligent scheduling and execution of one-time and continuously active tasks based on specific criteria, such as the time-of-use energy prices, energy availability, etc.
  - **Measuring consumption:** In order to provide detailed statistics on the energy use of the household, and manage scheduling and execution of tasks, USEM must be able to measure and monitor the energy consumption of all the connected devices.
  - **Conditional rules:** The system must support the possibility of defining conditional rules, for instance to perform actions when certain conditions are met. An example of such a rule is turning off the heating when nobody is at home.
  - **Remote control:** To control devices remotely, USEM has to provide a mobile interface to access various functions of the system. This would allow users to schedule tasks ahead of time, and then react to any problems, which may occur when tasks are executed by the system.
  - **User defined settings:** USEM must provide mechanisms for defining user settings. For examples, keeping a comfortable room temperature level, or saving as much energy as possible.

#### A. Architecture of USEM

USEM has a modular system architecture [36], consisting of three layers as shown in Figure 1.

- **The Ubiquitous Components Layer** consists of all the individual sensors, actuators and devices connected to the system. Sensors are used to measure environmental factors and energy consumption data, while the actuators are used by the system to control the connected devices.
- **The USEM Middleware Layer** combines the various third-party systems connected to the Ubiquitous Components layer, and exposes a unified platform-independent interface to all the layers above it. It provides basic functionality to control devices and retrieve energy consumption data for specific appliances. Additionally, it can also retrieve information from external sources (e.g., energy prices and weather forecasts).
- **The USEM Client Applications Layer** contains all external applications that communicate with the scheduling component or directly with the USEM middleware. Examples of such applications are provided below.

Figure 2 shows the UML component diagram of the internal structure of the USEM middleware layer. As can be seen, the middleware layer consists of five modules:

- **Hardware Interface Components:** are used to communicate with, and control, physical, as well as virtual,

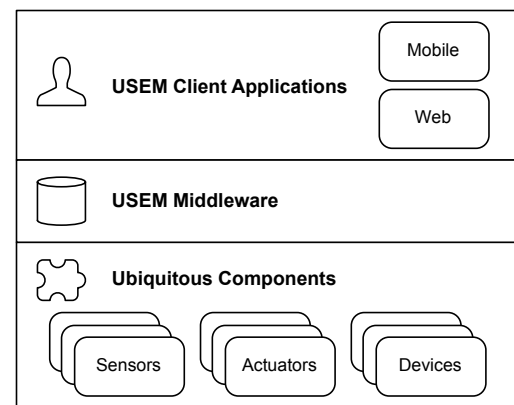


Figure 1: Architecture layers of USEM.

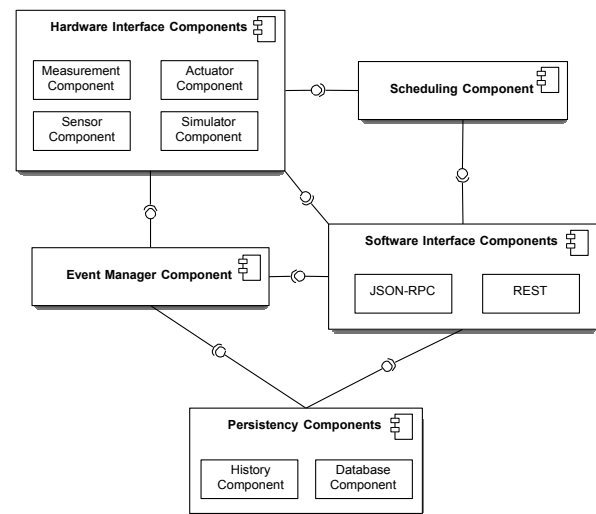


Figure 2: Structure of the middleware components of USEM.

parts of the system connected to the Ubiquitous Components layer. There are four types of such components: energy use measurement devices, actuators, sensors, and simulators.

- **Software Interface Components:** are used by client applications to access the functionality of USEM. We provide two such interfaces. JSON-RPC API [37] can be used to establish a two-way socket connection with the USEM middleware when socket connections are supported. Alternatively, the RESTful API [38] can be used for HTTP communication with the USEM middleware.
- **Persistency Components:** include a history manager, which periodically stores energy consumption data for each device, as well as its operating mode, who has used it, and where it is located in the building. USEM also keeps a database of its devices and hardware components (e.g., which device is plugged into which socket). To better deal with the large amount of data generated,

USEM uses the object-relational mapping framework EclipseLink, which stores the data in a local MySQL database. EclipseLink is an implementation of the Java Persistence API [39] that allows to easily map Java objects to relational database tables.

- **Event Manager Component:** deals with the large number of events generated by different parts of the system. Events are generated, for instance, when the current energy consumption of an appliance changes, when a sensor measures a change in the environment, or when a user manually switches a device on or off, etc. There are also many components that are potentially interested in such events. The history component, for example, must be notified about every change in the consumption value of a device in order to keep track of its consumption history. To deal with all this complexity, we implemented an event handling system based on the observer design pattern [40]. This allows every component interested in receiving a certain event to register for it with the central event manager. Whenever an event occurs, the event manager is notified, so that it can then forward the event and its attached information to any components registered for it. In addition to the original observer design pattern, we not only provide the possibility to register for a single event but also for a whole group of events. For example, a component might be interested in changes that occur in all devices in the living room. With our approach it is possible to register for all devices in the living room at once.
- **Scheduling Component:** is responsible for managing the schedule of all the tasks users have created in USEM. It always tries to find the optimal task execution order. The scheduling component has been implemented using JBoss Drools [41], which allows the creation of rules, as well as workflows and event-processing. USEM uses the JBoss Drools Expert framework to manage the execution of all its rules. The task scheduling and optimization is done by using the JBoss Drools Planner component. Rules and tasks are directly converted into the Drools Rule Language (DRL) format, readable by these components. The scheduler receives commands directly from client applications to create new tasks and to change the calculation parameters. When a scheduled task is due, the scheduling component interacts with the associated appliance through the hardware interface components to set the appropriate operating mode. The scheduler also manages continuously running devices like air-conditioning or water-heating and adheres to the user-defined levels for these devices.

### B. The underlying technology

As mentioned earlier, USEM relies on various sensors and actuators connected to its ubiquitous components layer, to manage all the household devices its users would like to control. To do this, we utilize a combination two existing technologies: HomeMatic [5] and Current Cost [2], which are described below.

- **HomeMatic:** is a home automation system designed to control off-the-shelf home appliances and devices. It consists of a central base station (Figure 3, left), which wirelessly communicates with and controls all its power socket adapters (Figure 3, right), to which individual home appliances are connected. The base station also wirelessly communicates with all its sensors. There are different kinds of sensors available: temperature sensors, motion detectors, light sensors, door and window sensors, etc. For controlling off-the-shelf devices, the appliance must be plugged into a HomeMatic adapter socket. There are simple on/off as well as dimmable sockets. Obviously, the limitation of simply cutting the power supply of devices is only suitable for simple devices like lamps, and is insufficient for more complex devices like a washing machine. Such devices must be controlled with a more advanced solution that provides the capability to set different operating modes. The HomeMatic central base station can be controlled either manually using a complex web-based user interface, or automatically through an XML-RPC API [42]. USEM uses this API to communicate with HomeMatic.
- **Current Cost:** was originally designed to monitor and record energy consumption data for an entire household. It can however also be used to monitor individual devices, by attaching a Current Cost jaw device around the power cord of each device (Figure 4, right). The consumption data can then be transmitted wirelessly by each jaw to a Current Cost base station (Figure 4, left). More recently Current Cost has launched a new product (called Individual Appliance Monitor) designed to measure the consumption of individual appliances, which looks similar to a HomeMatic adapter socket. Using either of these tools, energy consumption by each appliance can be measured every six seconds, and stored on the base station. The energy consumption history can be viewed on the display of the base station, or retrieved automatically using a serial data connection via USB. USEM uses this mechanism to access energy use data by devices connected to its ubiquitous components layer.

## IV. DESIGN OF THE CLIENT APPLICATIONS OF USEM

Based on the requirements specified in the previous section we identified a range of functionality to be supported by USEM. To make people aware of their energy usage, USEM would provide detailed statistics about the household's past energy consumption. For example, the overall consumption could be displayed for individual rooms, devices, or occupants of the house. These statistics would allow the users to analyse their consumption history and, thus, identify saving potentials. In some cases USEM might also be able to suggest actions that would lead to a decrease of energy consumption. Furthermore, USEM would support the user in putting theoretical energy saving ideas into practice. For instance, the user could schedule appliances to run when varying energy rates are the cheapest, or USEM could switch off devices when they are not needed (e.g., turning off the printer whenever the PC



Figure 3: HomeMatic base station (left) and socket adaptor for power outlets (right).



Figure 4: Current Cost base station (left) and jaw connected to a power-board (right).

is switched off). By providing an intelligent scheduling for energy consuming tasks USEM would also be able to use energy when it is available from off-grid sources (e.g., when the solar panels are generating electricity). Using a combination of these techniques USEM would attempt to ensure that energy usage peaks are avoided, maximum renewable energy is used when available, and overall power usage reduced in an intelligent manner without necessarily reducing comfort levels.

To interact with USEM we designed three different user interfaces: 1) a *web interface* for performing more complex tasks such as managing manual and automatic task scheduling, 2) a *tablet interface* to act as a control unit that could be used from around the house, and 3) a *mobile phone interface* that could be used to interact with USEM while on the go.

For each of these interfaces we identified specific functionalities that they would support. These were then used to design paper prototypes for the three interfaces.

We conducted an expert review of the paper prototypes with four experts, to evaluate the proposed interface designs and

functions of USEM. This evaluation resulted in a number of suggestions for improvements, which were used to modify the subsequent versions of the designs used for development of a working prototype.

## V. USEM PROTOTYPE SYSTEM

We have developed a functional prototype system based on the modular architecture described earlier. Due to the limitations of currently available home appliances, however, it has been necessary to manually modify some aspects of the interaction between USEM with such appliances. For instance, most existing washing machines cannot be automatically programmed to perform various types of wash cycles, so at this stage we can only turn them on/off, once the user has manually chosen their desired wash cycle. Similarly devices cannot be automatically recognized when connected to USEM, so we print and attach our own barcodes to devices and use these to identify individual devices.

As part of our prototype system, we have also developed three client applications based on the designs discussed in the previous section. These applications allow individual users to login to USEM, not only to interact with the underlying system, but also to allow USEM to monitor energy consumption by individual users, and to provide user-specific controls and information to individual users. Here we present an overview of each of these client applications and their functionalities.

### A. Web interface

As mentioned, the web interface of USEM provides higher-level access to the functionality of the system. It allows configuration, scheduling, and visualization of relevant information. Figure 5 shows an example screen of the web interface used for creation of a new task, which will be scheduled and executed automatically by the system. The web interface, along with the more intelligent components of USEM required for the automated energy consumption management strategies (e.g., task scheduling, etc.) have been described more fully elsewhere [43] and will not be discussed further here.

### B. Tablet interface

The tablet interface acts as a control and access unit for USEM. Although the current application has been developed for an Apple iPad, it is envisaged that it could also in the future be installed in flat-panel displays incorporated into furniture, picture frames or walls to act as an ambient device interface.

Figure 6 shows the home screen of the tablet interface, which is visible when the device is not being controlled by a user. This allows users to have a constant view of the most important information about their household, which encourages them to monitor their energy use. The home screen is customizable with several widgets to display information such as a list of currently running devices, up-to-date energy prices when available, etc. This screen also shows the energy usage target set by the user, and the current usage level, to motivate the user to keep their usage below their set target. If the target is being threatened, for instance when the user turns

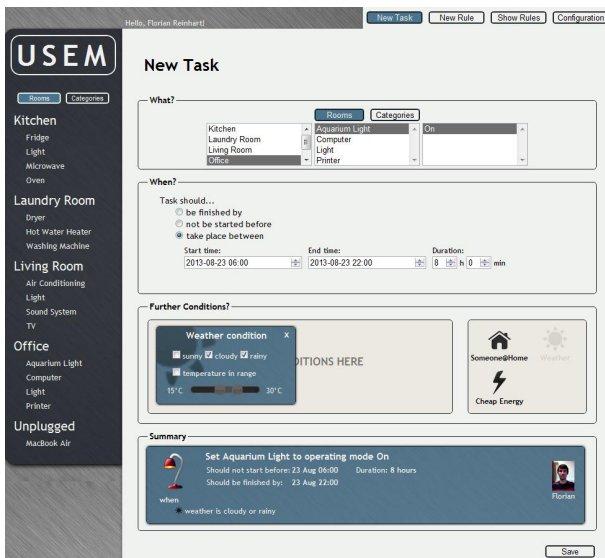


Figure 5: Web interface of USEM, showing a new task being created.



Figure 6: Home screen of the tablet interface of USEM.

on a device, they get a warning from the system giving them the option of turning off another device, which is not being used (if any) or not going ahead with their scheduled activity.

This interface also allows users to view their energy consumption information over the past year, month, or day. Figure 7 illustrates one of the energy usage visualizations. This information can be viewed in several different chart formats, and in various categories, such as for the entire house, different rooms, all users, different users, all devices, different category of devices, etc. This is another important element of the user interface in terms of encouraging energy usage awareness.

In addition, the tablet interface gives energy saving recommendations, based on past and current energy consumption data, to help users reduce their energy use. Figure 8 presents an example energy saving tips screen. On this screen the system

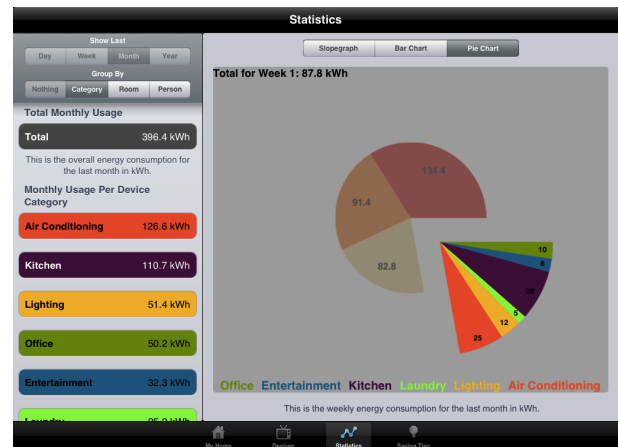


Figure 7: Usage information screen of the tablet interface showing a pie chart.



Figure 8: Energy saving recommendations and their consequences if applied.

suggests actions that would decrease the household's energy consumption, as well as calculating the savings that could be made if the advice is followed.

### C. Mobile phone interface

The mobile phone interface, developed for Apple iPhone, can be used to retrieve the status of home appliances or to interact with them remotely. It also notifies the user about energy usage events that occur while the user is away (e.g., a scheduled task cannot be undertaken because there is not enough renewable energy available). In such cases, the mobile phone interface provides suggestions (Figure 9) about how the problem could be resolved and gives the user the opportunity to decide what to do (e.g., cancel a scheduled task, or turn off another device).

Of course, the mobile phone interface can also be useful while the user is at home. For instance, it can be used

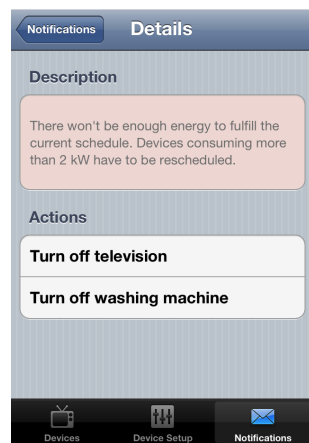


Figure 9: Event notification screen of the mobile phone interface.



Figure 11: The set-up used for the user evaluation.

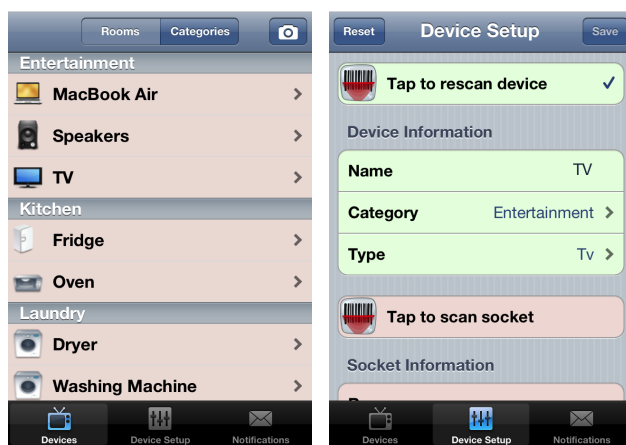


Figure 10: USEM devices (left) and new device set-up (right) screens of the mobile phone interface.

to remotely access any of the devices connected to USEM (Figure 10, left). Users can also directly interact with home appliances by scanning the unique barcode that is attached to each device when they are added to USEM. For example, this allows creating a new task for the washing machine right after the user has put the laundry into the machine. The mobile phone application also simplifies the initial set-up procedure for new devices, by mapping the barcode tags attached to power sockets with those of devices connected to them through a simple scanning process (Figure 10, right).

## VI. USER STUDY OF USEM

We conducted a user study to evaluate the usefulness of USEM and gauge if people would actually use a system like USEM to save energy if they had access to it. In the following sections, we describe this study and discuss some of its main findings.

### A. Methodology

The study was conducted at a usability lab, where the participants performed a series of tasks using the web, tablet, and mobile phone interfaces. To do the tasks the participants were provided with a laptop, an iPad, an iPhone, and model of a dryer and a computer as two home appliances (each with a barcode attached), as shown in Figure 11. We also attached a barcode to a power socket to make it recognizable by the mobile phone interface of USEM.

Each session started with a tutorial, which included some sample tasks similar to the actual tasks that the participants would perform after the tutorial. Participants were allowed to spend as much time as they needed to complete the tutorial.

The actual study session took about an hour in total, and was divided into three parts covering the use of the three interfaces of USEM. The sessions started with the web interface, as this was the most general part of the system and gave the user a comprehensive overview of USEM (for details of this part of the study and its findings see [43]). This was followed by tasks that users performed using the mobile phone and tablet interfaces.

At the end of each task the participants answered several questions related to the task and the tool they had just used. At the end of the session the participants completed a final questionnaire covering some questions about the users' overall impression of USEM.

### B. Study Participants

Twenty participants took part in this study. They were between 20 and 62 years old, with an average age of 35. Five of them were female and 15 male; 11 were students, two researchers, two managers, two office administrators and a housewife. Thirteen of the participants (65%) had previous experience using a multi-touch screen; 11 (55%) owned a smart phone and 4 (20%) owned a tablet device. All of the participants used a computer daily, none had any previous



TABLE I: Demographic of the study participants.

	No. of Participants	Percentage
<b>Gender</b>		
Male	15	75.00 %
Female	5	25.00 %
<b>Occupation</b>		
Student	11	55.00 %
Researcher	2	10.00 %
Other	7	35.00 %
<b>Experience</b>		
Multi-touch screen	13	65.00 %
Daily PC usage	20	100.00 %
<b>Own device</b>		
Smart phone	11	55.00 %
Tablet	4	20.00 %

knowledge of USEM or experience with any other energy management system. Table I shows a summary of the participants' demographic data.

### C. Study Tasks

As mentioned earlier, the study participants had to perform specific tasks using each of the different client applications of USEM. We asked the participants to perform the following tasks using the mobile phone interface on the iPhone given to them.

- 1) *m1: adding a new home appliance to USEM.* In this task the participants were asked to connect a computer given to them to USEM, by physically plugging it into the appropriate power socket, and naming it as "Private PC".
- 2) *m2: controlling a home appliance remotely.* In this task the participants had to turn off the television remotely.
- 3) *m3: creating a new scheduled task to let USEM execute it at a later time.* In this task the participants had to create a new task for a given dryer (see Figure 11) by scanning its barcode, and then scheduling the task to be completed by 8am the next morning using the "Delicate" dryer setting.
- 4) *m4: sending users a demo notification and asking them to react accordingly.* For this task the participants were sent a message (to the iPhone they were using) telling them that there was not enough energy available to perform a dryer task they had previously set up. To resolve this problem they were asked to turn off a device they did not need at that moment (in this case the computer) to make enough energy available for drying the clothes.

The participants then performed the following tasks using the tablet interface on the iPad given to them.

- 1) *t1: controlling a home appliance remotely.* In this task the participants had to turn on the television. USEM warned the users that they might not achieve their weekly saving goal because some other devices were already turned on. USEM recommended turning off other devices, which the participants then had to do in order to successfully complete the task.
- 2) *t2: exploring energy consumption statistics using a bar chart visualization.* In this task the participants were



Figure 12: Usage information screen of the tablet interface showing a slopegraph.

asked to use the bar chart to identify the week, in which the household had consumed the highest amount of energy. They also had to specify the amount of energy used during that week.

- 3) *t3: exploring energy consumption statistics using a pie chart visualization.* This task required the participants to use the pie chart to identify the device category that accounted for the most energy usage during week 4. They also had to specify the amount of energy used by that category.
- 4) *t4: exploring energy consumption statistics using a slopegraph visualization.* In this task the participants had to find out which device category had the largest increase in energy consumption during week 4 compared to the week before. They also had to specify the amount of this increase. To complete this task, the participants were asked to use the slopegraph. Figure 12 shows an example of type of slopegraph [44], [45] used in this study.

### D. Task Questionnaires

As mentioned earlier, after the completion of each task the participants were asked to answer a questionnaire. Two questions were common to all the task questionnaires. These were:

- 1) How easy was it to perform this task?
- 2) How useful would it be to have this functionality?

The participants answered these questions using a Likert scale of 1-7, with 1 being the least positive and 7 the most positive.

### E. Final Questionnaire

Once the participants had completed all the study tasks, they were asked to complete a final questionnaire, which aimed to measure their overall subjective impression of USEM. Table II lists the questions of this questionnaire, along with the 7-point

TABLE II: Questions of the final questionnaire.

No.	Question	Rating	
Q1	How easy were the visualizations on the iPad interface to understand?	1: very difficult	7: very easy
Q2	How likely do you think it would be that you would decrease your energy consumption with the help of the visualizations on the iPad?	1: very unlikely	7: very likely
Q3	Would you want visualizations like on the iPad to be a permanent part of your home?	1: definitely not	7: absolutely
Q4	How easy would it be for you to adapt using USEM for tasks where you do not have to change your daily routine very much? (e.g., create tasks for doing the laundry, instead of just switching the washing machine on manually?)	1: very difficult	7: very easy
Q5	Would you adapt your daily routine in order to use more renewable energy? (e.g., start cooking dinner an hour later?)	1: very unlikely	7: very likely
Q6	How often would you control a device directly or retrieve information about it using the bar code scanner on your mobile phone?	1: very rarely	7: very often
Q7	How often would you use your mobile phone to control your appliances remotely while you are away from home?	1: very rarely	7: very often
Q8	How often would you like to be notified on your mobile phone about what is going on in your household in terms of energy consumption?	1: very rarely	7: very often
Q9	How useful do you find the overall system with regard to efficient energy usage?	1: not useful	7: very useful

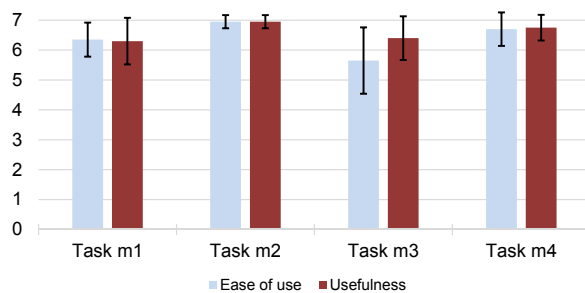


Figure 13: The average ratings given by the participants for the tasks performed using the mobile phone interface.

Note: error bars show the standard deviations.

Likert scales used for each question. The final questionnaire also asked the participants to provide any additional comments or ideas they might have had about USEM.

#### F. Study Results

1) *Results for the mobile phone interface:* Figure 13 provides a summary of the average ratings given by the study participants for each of the two questionnaire questions for each of the four tasks performed using the mobile phone interface. As the results show, the participants generally found the tasks easy to perform, and the functionality provided by the interface useful.

Task m3 was considered as being more challenging than the other tasks. However, the functionality needed to perform this task was still rated as being useful. It is also important to note that this task was the most abstract task, which relied on the intelligent scheduling components of USEM.

The ratings given to the difficulty of the tasks is further supported by the number of people who completed each of the tasks successfully. As can be seen in Figure 14, everyone completed tasks m2 and m4 successfully, while 18 people completed Task m1, and 17 people completed Task m3 (this being the most difficult task). Overall the results are very good, considering the fact that the study participants had never used an energy management system previously.

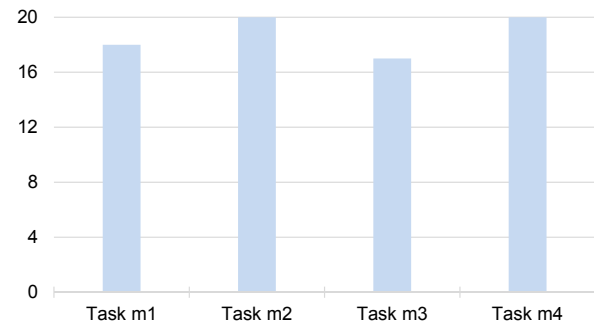


Figure 14: Number of successful completions for the tasks performed using the mobile phone interface.

2) *Results for the tablet interface:* Figure 15 shows a summary of the average ratings given by the study participants for each of the two questionnaire questions for each of the four tasks performed using the tablet interface. Since the difficulty of the tasks steadily increased, the ease-of-use rating for the tasks decreased slightly from Task t1 to Task t4.

However, in general all tasks have been rated as easy to perform with average ratings ranging from 6.30 to 6.75. The ratings given to the usefulness of the functionality provided by the tablet interface for performing each of the tasks showed a trend similar to that observed for the difficulty of the tasks. Once again, overall the participants found the functionality provided very useful.

In terms of the task completion, all the study participants completed all the tasks successfully (see the bars for Part 1 in Figure 16). However, three of the tasks (t2, t3, t4) also had a second part, which asked the participants to report an exact value (in kWh) for energy consumption using one of the three visualizations provided (bar chart, pie chart, slopegraph). As can be seen in Figure 16 (bars for Part 2), all the visualizations were less than perfect in terms of allowing the users to identify the correct energy consumption value, with the pie chart (Task t3) being the worst in accuracy.

3) *Results of the final questionnaire:* Figure 17 shows the average ratings given by the study participants to each of the questions of the final questionnaire. The results show that the participants had a generally positive view of the various

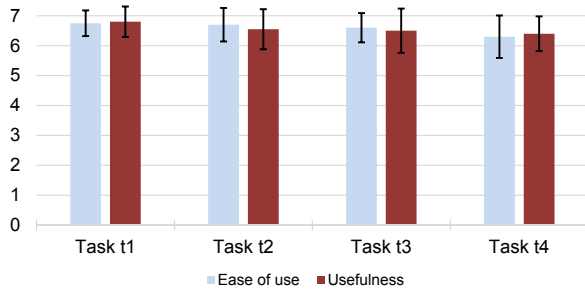


Figure 15: The average ratings given by the participants for the tasks performed using the tablet interface.

Note: error bars show the standard deviations.

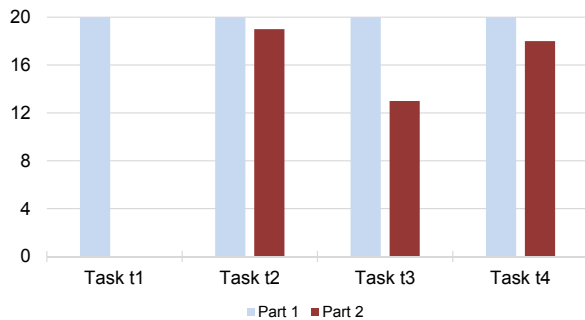


Figure 16: Number of successful completions for the tasks performed using the tablet interface.

Note: Task t1 had only one part.

components of USEM, its client interfaces, and its likely effect in their potential behaviour changes. In particular the participants found the visualizations of the tablet interface easy to use (Question 1), thought these would help them decrease their energy consumption (Question 2), and would like to have them in their homes (Question 3). Although still very positive, the participants were however less committed to using the mobile phone interface to remotely interact with their devices while away from home (Question 7), or receive information about their energy consumption (Question 8). Perhaps the most important finding we can conclude from the final questionnaire is that the participants thought that USEM would be useful in helping them use energy more efficiently (Question 9). It is also important to note that the participants thought they would use USEM to change their daily routines (Question 4) and adapt them in order to use more renewable energy (Question 5).

As mentioned earlier, the final questionnaire also invited the study participants to provide any comments and ideas they might have had about USEM. The following is a summary of some of the main points made by the participants in their comments.

- Many of the participants stated that they would like

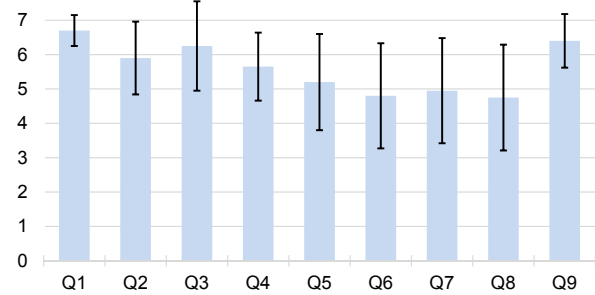


Figure 17: The average ratings given by the participants for the questions of the final questionnaire.

Note: error bars show the standard deviations.

to be able to determine what events they should be notified about. They feared that they would get annoyed or distracted by notifications if they did not have some control over the notifications sent to their mobile phone.

- Most of the participants especially liked the possibility of controlling all the appliances using a single interface, rather than using a variety of different user interfaces for controlling different home appliances.
- The participants confirmed that they do not know how much energy each of their appliances uses. They rate their energy usage awareness as relatively low. They liked the energy usage visualizations provided by USEM, and thought that these would assist them to better understand the power usage of their appliances.
- Several participants stated that they do not have a good understanding of the kWh measurement unit. Instead they would prefer some kind of visualization, which is easier to understand and does not require any technical knowledge. They also suggested to display dollar amounts, and setting the saving goal in dollars as well.
- One participant commented that he would like recommendations for a saving goal. In this participant's opinion, it is difficult to set a saving goal, since it might be hard to determine a realistic energy consumption limit. So, the system could provide a recommendation for a feasible saving goal based on previous usage data.

Further to these comments, which are directly related to the functionalities and client application interfaces of USEM, one of the participants raised the issue of security concerns over unauthorised people accessing and controlling their household appliances. Although USEM has not at this stage dealt with the issue of security, in other related research [46] we are investigating security of systems such as USEM.

## VII. PERSUASIVE ASPECTS OF USEM

It is important to note that tools and technologies, such as USEM, which aim to assist people with changing their behavior need to be "persuasive" in their approach. The idea of *computers as persuasive technology*, or "captology", was introduced by Fogg [47] to deal with the question of how

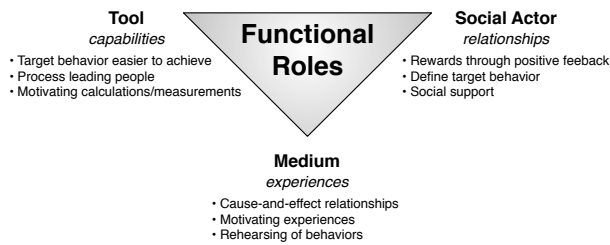


Figure 18: The roles computer technology can play in persuasive context, as defined by Fogg [48].

interactive computer technology could be used to persuade people to change their behavior or attitude. The functional triad, as defined by Fogg [48], is a framework that illustrates three roles computers can play in a persuasive context (Figure 18). These roles are categorized as tool, medium and social actor.

In the context of the work presented in this paper, we are mainly concerned with computers as persuasive tools. Tools increase capabilities by making the desired behavior easier to achieve, by guiding people through processes, or by calculations and measurements that motivate people to reach their goals. There are seven different categories of persuasive technology tools [48], which can be combined together in a single system or application.

- 1) **Reduction:** People can be persuaded by reducing complexity. A good example of a reduction is the *one-click buy* functionality provided by Amazon [49], which reduces the ordering process to a simple button click.
- 2) **Tunneling:** This is the process of leading a user step-by-step through a specific procedure. An example of tunneling is the ordering process of online shopping sites. Such a guided process can provide opportunities for persuasion along the way. For instance, an online shopping site can suggest other items of interest to the buyer during the ordering process.
- 3) **Tailoring:** This approach persuades through customization, by providing only the type of information which is relevant and interesting to the user. An example of this is customized newsletters sent to users offering them products that match their buying profiles.
- 4) **Suggestion:** This means providing suggestions at the right moment. An example of this is advertisements along a highway, that for instance place an advert for a restaurant near its physical location and not miles away.
- 5) **Self-Monitoring:** People like to control themselves and check whether they have reached a predetermined goal. An example of this is a heart rate monitor that can be used to monitor the heart rate during exercise.
- 6) **Surveillance:** People tend to change their behavior when they know that they are being observed. An example of this is messages like “How am I driving?” at the back of some delivery trucks, to ensure that the drivers know people can complain about their bad driving, so they drive more carefully.

- 7) **Conditioning:** Giving positive, or negative, reinforcement can have a persuasive effect. An example of positive reinforcement is being on the high scorers list in a computer game, which can persuade people to play the game longer to improve their placement on the list.

To measure the success of a system as a persuasive technology clearly requires a long-term study of the use of the system in real-life settings to see if it indeed assists its users with changing their behavior. Although we are yet to conduct such a study of USEM, we have attempted to analyze the ways, in which USEM might be able to play the role of persuasive technology listed above. Below, we provide a summary of this analysis.

- 1) **Reduction:** USEM reduces the complexity of the large volume of energy usage data, collected for many devices over an extended period, by categorizing it, and allowing the user to view it in a variety of forms.
- 2) **Tunneling:** USEM provides step-by-step guidance for dealing with the process of adding new appliances to the system, dealing with notifications, managing energy saving targets when they are breached, etc.
- 3) **Tailoring:** Energy usage information provided is tailored to individual users (i.e., their personal data), energy saving recommendations provided are tailored to each specific USEM installation and are always relevant to the context.
- 4) **Suggestion:** When USEM warns users about missing their targeted saving goals, it suggests what actions could be taken, for instance by giving a list of devices that could be turned off. Also, when USEM sends notifications to the mobile phone interface when scheduled tasks cannot be undertaken, it provides a list of suggestions that the user can select from.
- 5) **Self-Monitoring:** By measuring energy usage of each individual (when possible), USEM allows them to monitor their own current performance against targeted saving goals, as well as allowing them to monitor their past usage history in various statistical visualization forms.
- 6) **Surveillance:** Due to the fine granularity of energy usage data that USEM collects, the user knows (even when living in a house with others) that their consumption behavior is recorded and can be tracked by others when allowed.
- 7) **Conditioning:** By allowing users to compare their own energy usage behavior to others, as well as their set targets, USEM provides users with positive or negative reinforcements depending on their performance.

## VIII. CONCLUSIONS

In this paper, we have discussed the design and development of USEM, a system that aims to support the inhabitants of residential homes with the process of monitoring their energy usage, and making energy savings possible without necessarily reducing their comfort levels. USEM allows its users to connect and control their home appliances, as well as analyze and understand energy consumption information by

those appliances using a range of scheduling, notification, and visualization tools.

Our laboratory-based user evaluation of USEM has shown the potential benefits of its client applications, designed for web-browsers, mobile phones, and tablet devices, in providing the necessary means of assisting people with saving energy, as well as encouraging them to monitor and change their energy use behavior.

We have briefly analyzed the capabilities of USEM as a persuasive technology, by examining some the features of its mobile interface components against existing guidelines for the design of persuasive technology. Although this analysis shows that USEM satisfies these guidelines, it is important to conduct a more formal real-life user evaluation of the persuasive capabilities of USEM.

Our study has also identified a range of improvements that could be made to USEM, particularly in improving the type of visualizations it provides to allow the users to effectively access, analyze and compare their energy consumption data. This is an area of interest, which we are investigating further [23].

#### ACKNOWLEDGEMENTS

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