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Construction and Experimental Evaluations of User-Centered Power Consumption Management Systems in Home Environments

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Abstract

Construction of flexible and efficient energy management systems is urgently needed to address environmental issues such as climate change. Home energy management systems have thus far been limited since they only control consumer appliances based on sensed data. In this paper, we propose an architecture model for home power management systems, introducing a user-centered design to adapt to individual families. The proposed model includes a user satisfaction index called Efficiency of Service.

A set of smart outlets that mediate between home outlets and appliances facilitates the construction of an actual system. Smart outlets help in measuring the voltage and current values of the attached appliances, and in transmitting them to a home server, which then provides visualization and other services to the user. Finally, the user acts to reduce power consumption directly or indirectly and user satisfaction can be evaluated and fed back to the system.

In power monitoring experiments carried out in four actual homes, power consumption of appliances was measured and visualized for the residents. Along with the power consumption data collected from each home, user feedback was also collected via questionnaires, and the effectiveness of the service was evaluated through these experiments. Power reduction was found to average approximately 43%.

Keywords: *Smart outlet, power monitoring, visualization service, Effectiveness of Service, visual analog scale, user-centered design*

1. Introduction

Reducing greenhouse gas (GHG) emissions is a shared global challenge warranting high priority in the creation of a sustainable society. There is a clear need to incorporate information and communications technology (ICT) for this purpose; playing two roles known as greening of ICT and greening by ICT. The former involves reducing electricity consumption in ICT usage and conserving resources in ICT equipment, while the latter refers to utilizing ICT to help reduce GHG emissions by improving energy consumption in sectors such as production, transportation, office, and home.

In the transportation sector, progress in electric and gas vehicles is contributing to GHG reduction. In factory and other production, the introduction of monitoring and control systems achieves strong results because cost reduction is impelled by the need to improve the company's financial results [1], [2]. Recently, model-based power monitoring techniques for power provisioning have been developed at a datacenter scale [3]. Understanding of power usage dynamics is expected to inform choices regarding power management and provisioning policies, while quantifying the potential impact of power and energy reduction opportunities.

On the other hand, energy management systems in home environments have been left behind [4]. This reflects difficulties in introducing unified solutions into individual homes because of their differing physical layouts, family members, and life patterns. Nevertheless, this challenge was taken up in the development of Home Energy Management Systems (HEMS). Inoue et al. [5] introduced home network architecture aimed at automatically controlling appliances and providing information for energy saving. Their system, in which networked appliances are equipped with control and monitoring capabilities, controlled air conditioners so they could optimally set the temperature value, air flow rate, and operation mode based on the sensed external temperature. The system was, however, only demonstrated in field operation and no evaluation by actual users was conducted HEMS studies to date have largely tended to lack user evaluations; yet to make a system practical, a user-centered design or user-in-the-loop evaluation is needed.

In addition to user-centered design, construction of home energy management infrastructure is essential. Home appliances generally have to be implemented with specific network protocol stacks in order to be controlled by HEMS [5], and these stacks prevent easy and flexible installation of energy management systems in the home environment. Users with legacy appliances in their home must modify them or buy new appliances. Size and cost limitations also complicate implementation of the protocols for simple appliances. We therefore proposed and developed a smart outlet device with voltage and current sensors, a power control circuit, and a network module as a component of the home energy management infrastructure [6]. This can be attached to any kind of appliance to monitor its power consumption.

This paper addresses GHG reduction in home environments, focusing on electricity consumption as energy to be managed. Based on user-centered design and home energy management infrastructure, we propose an architecture model for a power management service in the home environment and develop an actual system. The proposed energy management system integrates power monitoring, wireless networking, and visualization with home residents' feedback. This leads to effective and user-proactive energy saving with little additional cost and few deficiencies caused by energy control. While most previous HEMS attempts aimed to control appliances directly, sometimes against the users' intent, the proposed system realizes intentional control by users for appliances via a visualization service. The system was introduced in four homes to evaluate its effectiveness.

This paper is organized as follows. Related work is reviewed in section 2 and section 3 describes the proposed system, including the total architecture model and deployment. In section 4, the proposed system is applied to experiments in actual home environments and the results are reported. After a discussion of the evaluation of the experimental results in section 5, section 6 concludes the paper.

2. Related Works

Energy monitoring, control, and visualization are the main components in home energy management. Energy monitoring is typically realized by sensing the power consumption of each home appliance. Based on sensing data on energy consumption, energy control is performed either automatically or manually. Visualization of energy consumption provides a real-time or summarized view. This helps residents understand how the energy is used and the change of energy consumption over time.

Power line communication (PLC) is a promising means of collecting power consumption information from each appliance [7]; however, as mentioned, size and cost considerations make it unrealistic to install PLC modems for every appliance. An alternate solution is an adapter-type monitoring device – a smart tap. One of the initial and typical smart taps developed for research was Plug [8], which not only has an electrical current sensing function but also a wide range of sensing modalities such as sound, light, vibration, motion, and temperature. Though Plug could be applied to a range of situations, its node size was comparatively large (approximately 20 cm × 7 cm × 12 cm) and it was considerably heavy (approximately 1 kg). This makes it unsuitable for use in a home environment. Recently, Song et al. [9] introduced a wireless power outlet system that enables remote control of home appliances. The module included ZigBee radio in its architecture, and applications are limited to switching home appliances on and off.

Saving energy is a primary target of energy control. Energy usage can be controlled automatically based on appliance activity states, which are learned from sensing appliance energy consumption, environment temperature, network traffic, and other such information. Oh et al. [10] proposed a power-saving system with power sleep control for home appliances, notably for the Internet Protocol Television (IPTV) service, by monitoring network traffic. Tompros et al. [11] provided standby appliance management to save energy by efficiently switching off standby devices. Though automatic switching-off of appliances seems to be effective for saving energy, it sometimes clashes with user needs, since each user's physical and emotional circumstances will vary. Further studies are said to be necessary to implement automatic appliance control into real-life home environments, and user-in-the-loop design is needed first. Standby appliances also cannot be turned off because of their timer function.

In recent years, energy visualization has attracted a great deal of attention [12]. This concept has been developed from simple approaches, such as displaying the energy consumption levels at the power meter, to integrated user-interactive information systems, and it is suitable for user-in-the-loop design. Eco-visualization [13] provides strategies for localized energy conservation that combine both artistic and scientific information to produce new forms of dynamic data representation. Examples include incorporating energy usage displays into household items such as clocks or power cords and developing abstract and informative art as shared eco-visualizations. Wood and Newborough [14] consider display location, motivational factors, display units (such as kilowatt-hours, dollars, or grams of CO_2), display methods (numerical and diagrammatic), time scales, and categories of use. Two display types are discussed: central (one per home) and local (specific to the location of an individual energy-use event). Classification of energy-consumption information in the home is thought to encourage effective energy-saving efforts. Holmes [13] aims to realize simple yet effective information-visualization systems to help users understand their energy use without having to become technical experts, electrical engineers, or control room operators. Though much progress has been made in energy visualization, little of it has integrated home appliances with a network and provided a user-interactive energy management system with energy-saving services.

Work has also addressed total system implementation. The Energy Aware Smart Home [15] presents a middleware framework that facilitates intelligent communication of heterogeneous embedded devices. Users can interact with the system via both stationary and mobile interfaces. For each device the current consumption is displayed in watts, cost per hour, and cost projected over one year using an adjustable average per-day usage time. Costs are calculated taking into account the electricity price, which depends on the time of day. AIM [16], which is a Small and Medium-scale focused Research Project (STREP) of the ICT Work Programme under the European Community's 7th Framework Programme (FP7), attempts to manage energy consumption in domestic environments in real-time. The constructed home network can be operated by the home's residents, and provides services and functions exposed to an outside network for device discovery and active configuration. However, this work mainly focuses on network architecture design, and there is no evaluation of its impact on energy saving. The specific network architecture may be too complex to enable easy adoption for the home.

3. Proposed System

An architecture model for a home power management service is proposed along with a user-centered design principle. Our power consumption monitoring device is then introduced as the sensor network infrastructure. Using the device, we develop a system of home energy management that can easily be installed in any home environment.

3.1 System model

First, a total architecture model is proposed including a sensor network, service manager, user service interface, consumer appliances, and users. The model is presented in Figure 1.

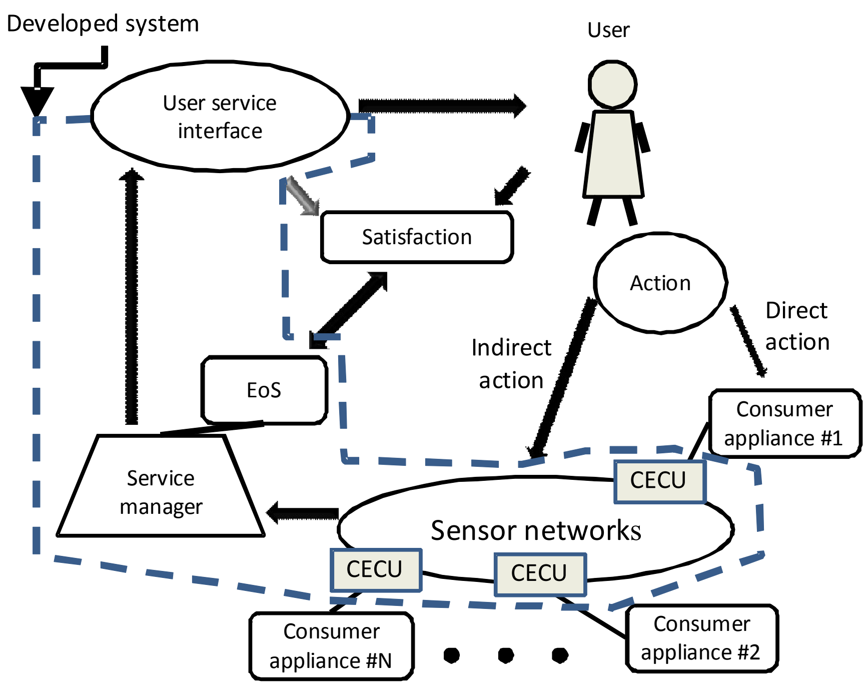

Figure 1. Total architecture model of power management service

A sensor network that can connect any kind of consumer appliance for monitoring is essential as one function of the home energy management infrastructure. For energy management, as a minimum, the current consumed by the appliances should be measured because voltage is relatively stable. Usually it is desirable to measure both current and voltage and transfer that to the service manager via the sensor network. The communication media of the sensor network is not specified or limited. In a home network environment, however, wireless networks such as ZigBee and PLC are promising. The service manager processes and manages the collected data and reports them to the user, and an interface between the user and service manager is needed; this is the user service interface in Figure 1. One important role of this interface is visualization of the monitored data. The information provided via the user service interface rouses users' action and explicitly or implicitly aligns with their sense of satisfaction.

In an actual example of power consumption monitoring, the service manager depicts the collected data in a graph or provides advice on power conservation. This information is transmitted to the user via an interface with visualization. On receiving this information, the user recognizes and comprehends the power consumption status and can control the power usage of consumer appliances or change an appliance's position to conserve power. Consumer appliances' situations change as a result of users' actions, as does the monitored information. Users evaluate the change and this is reflected in their sense of satisfaction.

In the area of networking services, indices on service evaluation and user satisfaction are related to Quality of Service (QoS) or Quality of Experience (QoE). In the model in Figure 1, it is not appropriate to introduce the concept of QoS or QoE because the general relational tendency between the system operation and user evaluation is not clear. Yet ultimately there is a need to accumulate real experimental data.

Instead of QoS or QoE, an index is introduced in this paper to evaluate how much power consumption is reduced. This is named Efficiency of Service (EoS), and it plays a mediation role between the system performance and user satisfaction.

3.2 CECU

A monitoring device called a Communication and Energy Care Unit (CECU) has been developed for the home power management service [6], and is shown in Figure 2. A CECU is a smart outlet with voltage and current sensors, a power control relay circuit for appliances, micro-controller, and network module. It is attached between the home outlet and appliances, measures the voltage and current values of the attached appliance, and sends them to the home server.

Figure 2. Communication and Energy Care Unit (CECU)

A CECU is about 103 mm × 63 mm × 40 mm and weighs around 200 grams. The micro-controller in the CECU converts analog signals from the sensors to digital values, extracts signal features, and controls the relay. When an appliance database is prepared, the CECU can recognize the type of appliance by using measured voltage and current values.

3.3 System setup as a Bit-Watt system

Using a CECU lets us actualize the architecture model shown in Figure 1 as a real-life home power monitoring system, called a Bit-Watt system. This system, presented in Figure 3, consists of a home server and a number of consumer appliances, and corresponds to the area enclosed by the dashed line in Figure 1. A home server and user interface controller are prepared for the home power management service. Two types of CECU—a coordinator and an end device—are attached to the home server and consumer appliance, respectively. As described above, the end devices are attached to the consumer appliances. The coordinator, however, is connected to the home server via a USB cable.

The coordinator and end devices communicate via wireless links. The networking of home appliances is realized by adopting a star topology wireless network based on IEEE 802.15.4, a low-cost, energy-efficient wireless communication standard. Wireless connection eases the setup of a home network. The Carrier Sense Multiple Access (CSMA)-based Media Access Control (MAC) protocol allows contention-based media access for each home appliance, and enables the random and arbitrary start of communication for home appliances.

The collected power information is periodically sent to the coordinator from the end devices. The coordinator stores the collected information as log data and processes it to provide, for instance, a visualization service. The coordinator can also control an appliance according to commands from the home server if necessary. The home server and coordinator correspond to the service manager in Figure 1.

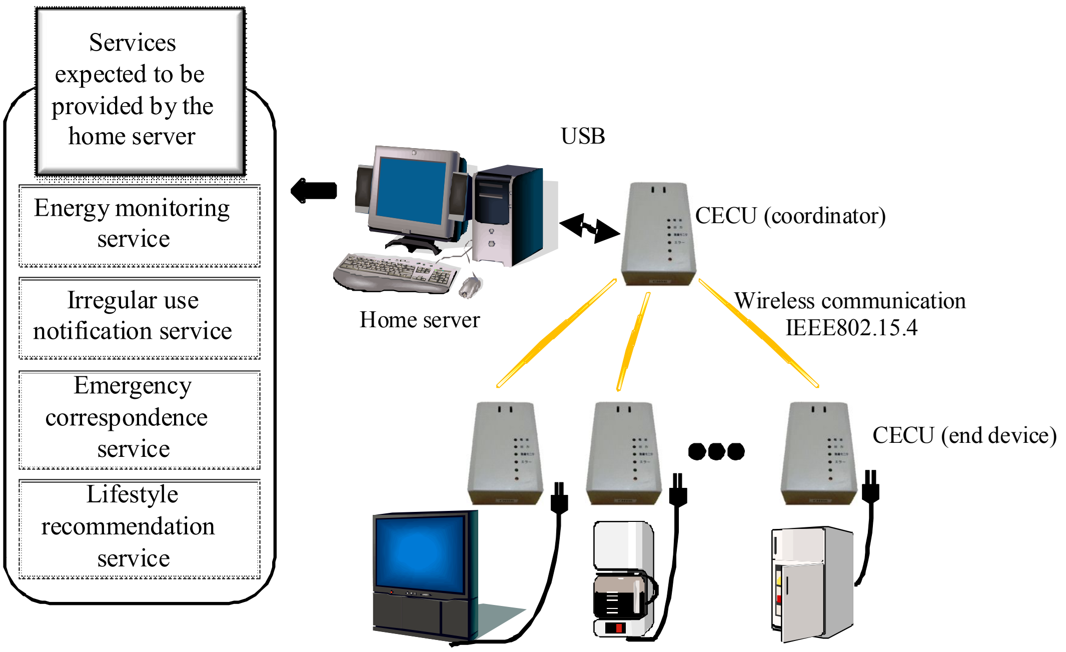

Figure 3. Total experimental system: Bit-Watt system

4. Experiments in Actual Home Environments

The deployed system is versatile enough to install in any type of home. To collect real-life experimental data, we set up the system in four different family homes and collected actual power consumption data and feedback information from the family members.

4.1 Experimental specifications

The Bit-Watt system presented in section 2 was introduced in four homes and actual power consumption data were collected. A visualization service was also provided to the home residents and evaluation data for the service were collected. Table 1 shows the composition of the families.

Table 1. Composition of experiment's families

	Composition
Family A	Parents, daughter, son
Family B	Parents, son
Family C	Parents, daughter, son
Family D	Parents, mother of husband, daughter, son

In the experiment setup shown as in Figure 3, one coordinator and 10 end devices of the CECU system were introduced in each home. Power consumption data from the consumer appliances attached to the CECU end devices were collected and appliance operation log data were recorded so as not to disturb the normal life patterns of the family members (subjects). Two scenarios, S1 and S2, were conducted in one experiment, each taking two hours. The purpose of running two scenarios was to find out the effects of power consumption reduction via a power visualization service.

In S1, the subjects led a normal life without watching the visualized power consumption information. In S2, the subjects watched this information and led their lives with the intent of increasing their levels of satisfaction. In other words, subjects are usually motivated to reduce power consumption when presented with this monitoring data. Figure 4 shows the room layout and appliance arrangement in Family B's home as an example. Figure 5 also presents an example of a monitor display, in which each bar shows power consumption by individual appliances. On the other hand, Figure 6 shows the time-series power consumption of the selected appliance, in this case an electric carpet. Subjects were able to deliberately switch the display content in the total power consumption display, the power consumption of each appliance, and time-series power consumption of any selected appliance.

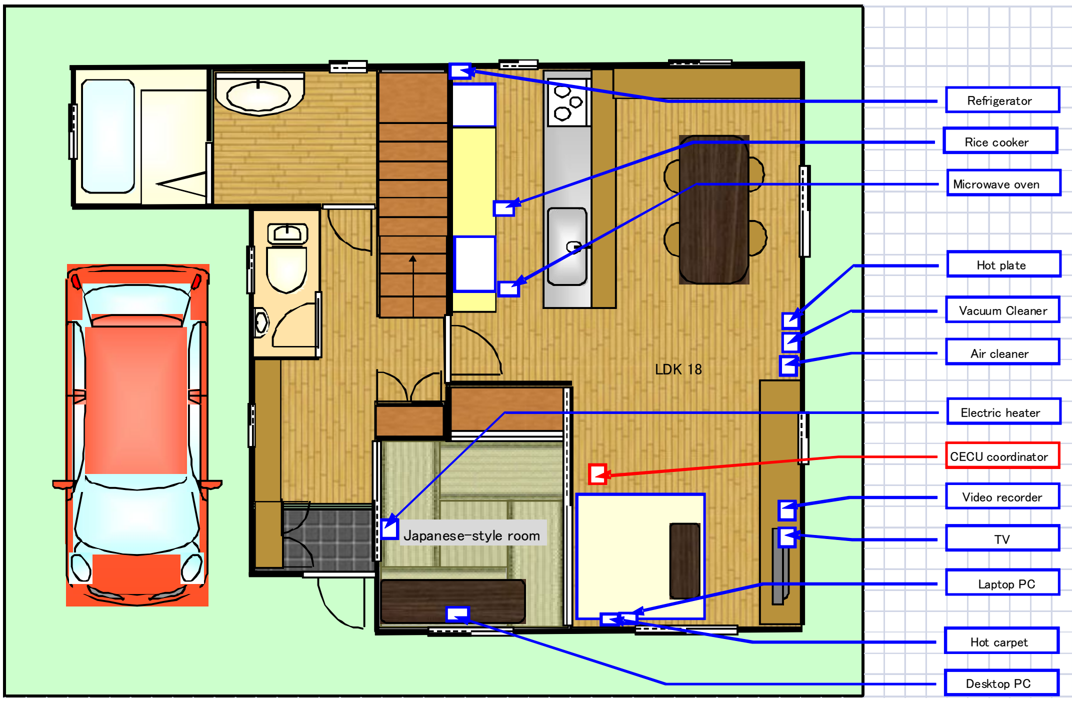

Figure 4. Room layout and appliance arrangement in Family B home

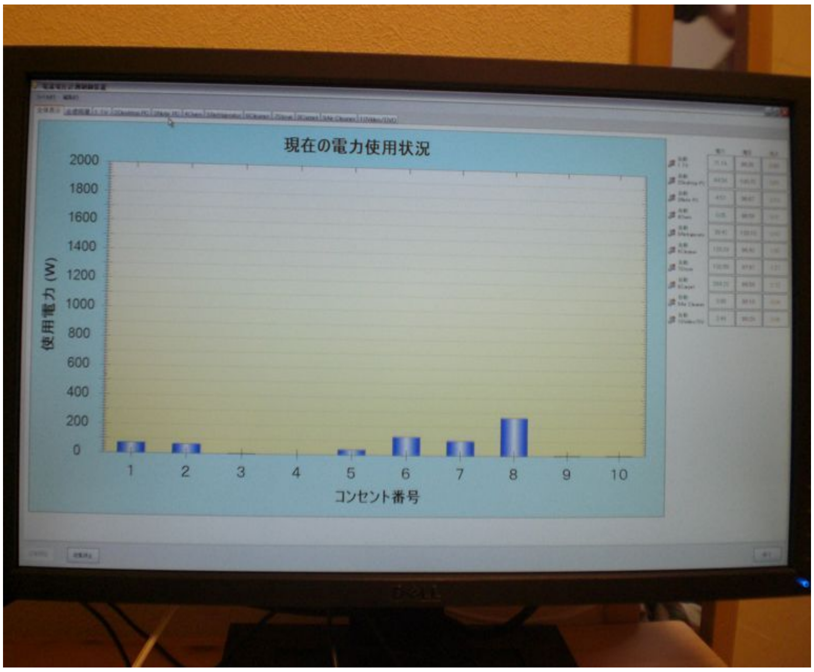

Figure 5. Monitor showing power consumption of each appliance

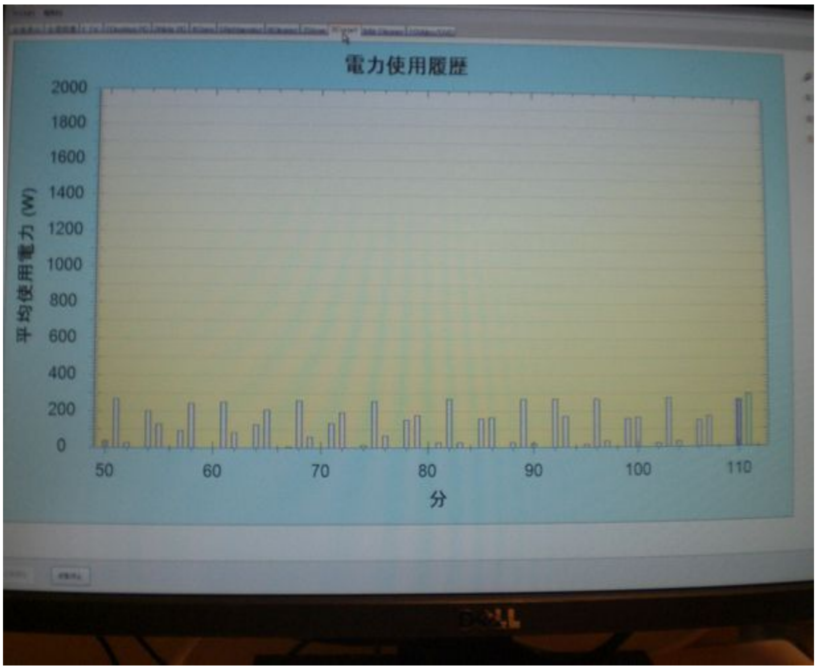

Figure 6. Monitor showing power consumption of selected appliance (electric carpet)

4.2 Experiment results

Part of the data measured by CECU is depicted in Figure 7 for scenario S1 in Family B's home. Table 2 also shows an example of the measured data in the same situation. As shown in the table, the voltage data are relatively stable, but sometimes fluctuate by a few percent from the 100V baseline. Standby power consumption can be estimated from the current measurement data.

The EoS in Figure 1 can be defined based on the difference between S1 and S2. Since the distinction is whether or not the subjects acted without monitoring power consumption, the difference between the two is considered to be the effect of user behavior being influenced by the visualization service. However, since the use of cooking-related appliances (microwave, rice cooker, hot plate) was irregular and power-consuming, such appliances were removed from the calculation in order to maintain a fair comparison.

Consequently EoS is defined as follows.

EoS = (total consumed power excluding cooking-related appliances in S1) - (total consumed power excluding cooking-related appliances in S2) (1)

It can be said that the larger the EoS is, the more effective the visualization service. The reduction rate RR is defined as follows.

RR = 100 x EoS / (total consumed power excluding cooking-related appliances in S1) (2)

Table 3 presents the EoS and RR of each family.

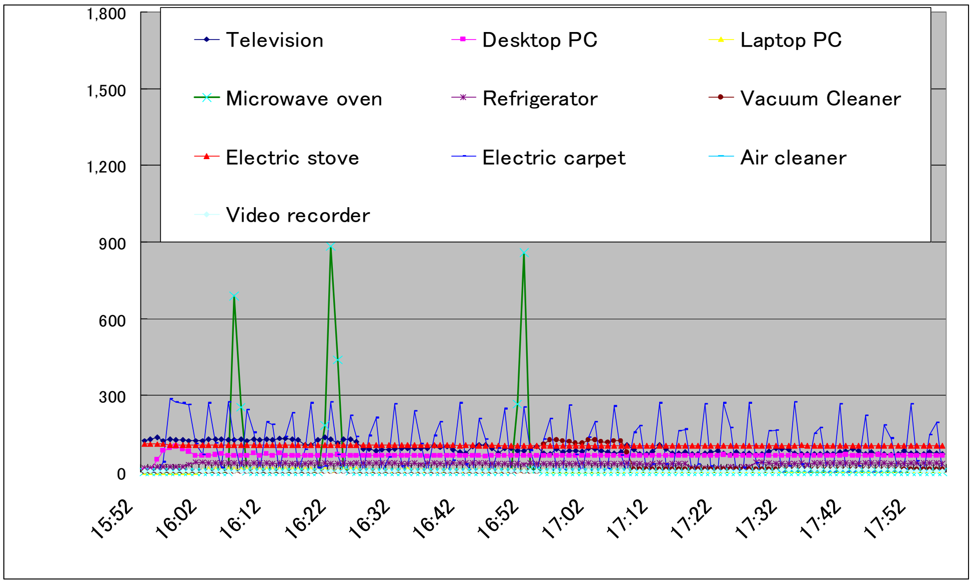

Figure 7. Part of measured data

Table 2. Example of measured current and voltage data

Appliance	Television	Desktop PC	Laptop PC	Microwave Oven	Refrigerator
Measured current (A)	1.07	0.62	0.13	0.11	0.41
Measured voltage (V)	102.22	101.53	98.44	102.94	100.07

Appliance	Vacuum Cleaner	Stove	Electric Carpet	Air cleaner	Video Recorder
Measured current	0.01	1.57	0.02	0.10	0.07
Measured voltage	100.07	99.67	101.68	99.76	100.87

Table 3. Family EoS and RR

	***EoS* (kW)**	***RR* (%)**
Family A	893	45.4
Family B	1,188	57.3
Family C	1,652	42.9
Family D	6,584	27.8
Average of *RR*		43.4

4.3 Subjective questionnaire

We issued questionnaires asking about intents, attitudes, and effects of energy-saving.

The first questionnaire was based on the visual analog scale (VAS) and consists of questions 1-9 listed in Table 4. VAS is an instrument that seeks to measure a characteristic or attitude believed to range across a continuum of values, and cannot easily be measured directly. One of the most common cases is measurement of the amount of pain a patient feels.

In operation, a 100 mm horizontal line, anchored by word descriptors at each end, is used as a VAS. An instance of VAS is presented in Figure 8. The anchored words at both ends usually have opposite meanings. Subjects mark the appropriate point on the line as that which represents their perception of the current state. The VAS score is determined by measuring in millimeters from the left or bottom end of the line to the point that the subject marks.

Table 4. Questions used in VAS-based subjective questionnaire

Q1	Do you usually think about and practice electric energy conservation?
Q2	Do you need CECUs in your life (without considering the cost)?
Q3	How do you feel about the size of the CECU end device?
Q4	Do you want to continue to check power consumption visually?
Q5	Do you have interest in energy or resource conservation not only for electricity but also for gas and water supply?
Q6	As a result of these experiments, do you intend to continue practicing energy conservation?
Q7	Do you intend to buy new energy-saving consumer appliances?
Q8	Do you want to check the power consumption of the appliances that the CECU cannot measure, such as lights?
Q9	How do you feel about the weight of the CECU end device?

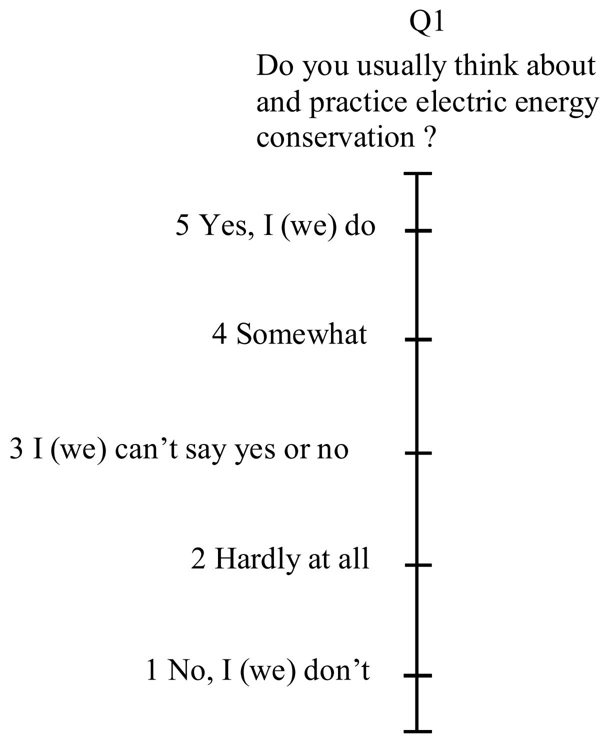

Figure 8. Questionnaire sample

The CECU system was evaluated subjectively by use of VAS. The VAS-based questionnaire was collected from four families, and is summarized in Table 5. The second, third, and fourth columns show the averaged, minimum, and maximum values of VAS for questions Q1 to Q9. The results are discussed in the next section.

Table 5. Family EoS and RR

	Average	Min.	Max.
Q1	56.25	23	81
Q2	64.75	43	81
Q3	91.25	78	99
Q4	59.00	42	80
Q5	85.25	80	92
Q6	74.75	65	90
Q7	65.75	40	83
Q8	67.25	50	92
Q9	73.00	59	93

The second questionnaire is based on the free description scheme and consists of questions 10-15 listed in Table 6. We asked these questions because it is impossible to ask interrogative questions with the VAS-based questionnaire. Though few details were obtained, interesting comments were provided for Q12 regarding Quality of Life (QoL) degradation. These include the following.

-When the hot carpet was turned off to save energy, the room felt a bit cold.
-Reducing the TV's brightness made it harder to watch, but I got used to it after a while.
-It's annoying to unplug appliances in order to save standby power.

QoL should be considered to include sensory and physical influences from the standpoints of perception and operation.

Table 6. Questions used in free description subjective questionnaire

Q10	What new findings did you make during the experiment?
Q11	What ideas about energy conservation did you gain through the experiments, and why?
Q12	What was your level of Quality of Life (QoL) degradation; i.e., How much inconvenience did you feel when you made efforts toward energy conservation?
Q13	Apart from what you did in the experiments, what strategies do you want to adopt in your life for energy conservation?
Q14	What do you think is an appropriate price for a CECU system?
Q15	Please tell us any other impressions you had of the experiments apart from the above questions.

5. Discussion

From an engineering standpoint, the CECU system was successfully installed in actual, typical homes, and accurately collected power consumption data. As an energy management service in a home environment, the visualization service was implemented and the subjects took part in two scenarios, with and without using it. Going by EoS as defined in this paper, the apparent effect of the service was approved; i.e., the visualization service was effective in reducing power consumption. This is only an initial step in experiments in actual home environments and more trials should be conducted, yet the visualization service could be one approach to tackling the greenhouse gas issue.

Subjective evaluations of the CECU system can be read in the summary of the VAS-based questionnaire in Table 5. Questions 1, 5, and 6 are related to energy conservation. Q1 concerns pre-experiment attitudes, while Q5 and Q6 deal with post-experiment opinions. Though answers varied before the experiments, all families reflected positive attitudes afterward. One explanation could be that services that support energy conservation are generally desired and the CECU can serve as one of these.

On the other hand, the VAS values for questions 2, 4, and 8 are not particular high, although these questions are directly related to the CECU system or visualization service. This seems to have been caused by disparities among individual families. Therefore the tendencies of each family need to be analyzed.

In the case of family D, which showed the smallest RR, the values of questions 1, 2, and 4 were also the lowest. The interpretation of this is that the visualization service was unsuitable for that family, though its members were interested in energy conservation.

Families A, B, and C showed relatively high VAS scores. The scores for questions 4, 7, and 8 varied for these families. Since these questions were related to future attitudes toward energy conservation, it was found that more adaptive services should be prepared for each family.

The VAS for Q5 showed high common scores for the four families. Total energy conservation management is required, including gas and water supply.

Future work will include the development of questionnaires and feedback regarding the system's operations.

6. Conclusion

To address the global greenhouse gas issue, we proposed an architecture model for a home power management service. Since the proposed model is based on a user-centered design, it enables reduced power consumption of consumer appliances without diminishing user satisfaction. The inclusion of indices for user satisfaction was a novel point in the model, and the paper also defined the EoS index.

By using smart outlets apart from any specific protocol, an actual system can be constructed quite readily. We implemented a Bit-Watt system using CECU, and a visualization service for power consumption of consumer appliances was developed for home environments. Useful user interfaces are installed to enable users to switch the display content among total power consumption, power consumption of individual appliances, and time-series power consumption of selected appliances.

Actual experiments were conducted in four individual family homes to evaluate the system's effectiveness. In addition to collecting power consumption data from the two scenarios, user feedback was collected through the experiments via a questionnaire. Based on EoS computation, the experiment achieved a 43.4% power reduction. The visualization service was found capable of contributing to GHG reduction, and more adaptive mechanisms for each family are needed to make the service more flexible.

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