The energy conservation and indoor environment improvement effect in a home with an environment visualization and management system

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Abstract. In recent years, HEMS (home energy management systems) have received attention as energy conservation measures, and are being adopted increasingly in smart houses. The Home Environment Visualization and Management System was developed by the author’s laboratory. The purposes of this system are to raise residents’ interest in the indoor thermal environment, encourage the use of passive control methods, and promote awareness of health, safety, and energy-saving in the home. In our proposed system, a dedicated website for each home, an LED indicator that shows indoor and outdoor temperature by color level, a real-time advice display function, and a weekly environmental report were prepared. In the weekly report, a comparison graph of power consumption with other homes was shown. In this study, a verification of the effects of this system, intended for about twenty subject homes, was conducted. The main results of the system operation are as follows:
1) The number of times the website was viewed increased during the summer and winter, though the browsing logs differed greatly among residences. This demonstrates that it is important to provide easy-to-use information to promote browsing.
2) In the log indicating reactions to the real-time advice, a positive reaction of at least 80% was confirmed. This indicates that providing advice in real time is effective in encouraging environmental adjustment behaviors.
3) From the answers to a questionnaire about the weekly environmental report, an energy-saving effect was obtained as power consumption increased. This shows that offering comparisons with other homeowners is effective in encouraging energy conservation.
From these results, it was confirmed that the website, the LED indicator, and the real-time advice were useful for promoting environmental adjustment behavior. In addition, it was confirmed that the weekly environmental report was useful for promoting energy-saving behavior.

1. Introduction
Among the household energy-saving measures in Japan, a system known as the Home Energy Management System (HEMS), which is being introduced in an increasing number of newly built residential buildings constructed in recent years. Japanese government aims to put HEMS into every home in Japan until 2030. It focuses on controlling ACs and lights and measuring and displaying power consumption and generation. In my laboratory, we worked on the development of a system to visualize information about the indoor and outdoor environment that will encourage inhabitants to engage in environment-regulating and energy-saving behavior and supplement the HEMS with historical information about the home. For this report, we implemented the system we developed in more than 20
homes for over half a year to determine whether the behavior of the subjects changed, their environment improved, or they conserved energy. We then analyzed the factors that influenced this.

2. Overview of our system

2.1. Overall composition of the system

Figure 1 is a diagram of the system we have developed. It measures the following: indoor and outdoor temperature and humidity, particulate matter concentration, indoor CO\textsubscript{2} concentration, mean radiant temperature, window/ground surface temperature, and electricity consumption. Information from each sensor is measured at 1-min intervals and transferred via a ZigBee protocol to the base unit. From there, it is sent over an in-home router and stored on a server where the measurements and a graph of the data can be browsed via smartphone at a dedicated website.

![Diagram of the system](image1.png)

Figure 1. Diagram of the system

2.2. Visualization site

Figure 2 is an example screenshot of the visualization website. The home screen displays the current temperature and electricity consumption, and the user can also see the past graph for each item. Each page also randomly displays various helpful tips and advice on how to regulate the environment and conserve energy.

![Example screenshot of the visualization website](image2.png)

Figure 2. Example screenshot of the visualization website
2.3. LED indicators
The system is equipped with LED indicators to make it easy to monitor indoor and outdoor environmental conditions. Indoor and outdoor temperatures are shown in color under normal conditions, and the LEDs flash if there is a warning.

2.4. Real-time advice
The system can give “real-time advice” with the goal of encouraging inhabitants to regulate their environment for their comfort and health. For each piece of advice, there is a defined threshold (Table 1). When its condition is met, an LED indicator will flash and the site will display specific advice. The indicator is set to flash when there is a health warning, e.g., for heatstroke, dehydration, and high concentrations of CO₂ or particulate matter. The advice screen also displays buttons such as “Activate now” and “Out of the house,” by which the response of the subject to the advice can be confirmed later.

2.5. Weekly environment reports
We created “weekly environment reports” that we printed and distributed to subjects a way for them to reflect on the comfort in their home and their energy-saving behavior (Figure 3). The reports show information in four areas: (1) weekly electricity usage and comparison with other housing units; (2) electricity usage for every day, and average effective temperature in the living room when occupied, to show the balance between energy conservation and comfort; (3) fluctuations in temperature/humidity in the living room over time and when the system gave advice; and (4) an overall comment for the week to advise subjects about energy conservation and comfort.

Table 1. Defined threshold of “Real-time advice”

| Contents of the advice | Defined threshold |
|------------------------|------------------|
| 1 Outdoor Dust (μg/m³) | 600 ≤ Outdoor PM10, 35 ≤ Indoor PM2.5 |
| 2 Weather (℃)           | 28 ≤ Indoor temp. ≤ 30 ≤ Outdoor temp. |
| 3 Sun shield            | 28 ≤ Indoor temp. ≤ 30 ≤ Outdoor temp. |

Figure 3. Weekly environment reports
3. Overview of the experiment using the system

3.1. Overview of subjects

Table 2 shows an overview of the homes of the subject. The system was installed in residences A–K after July 2017 and in residences L–U after July 2018. Many of the homes in the Urawa-misono area are newly built, have high-grade heat insulation (UA value: 0.4-0.5W/m²K), and belong mainly to child-rearing households. Many of the other homes, which have varying dates of construction, belong to the elderly. In the Urawa-misono area, we recruited participants by combining the houses in each block together and explaining how the system worked. Many of the houses where we installed the systems in 2018 were suggested to us as candidates by designers and contractors, thanks to cooperation with a non-profit organization in Saitama Prefecture. We explained the system in detail to subjects when we installed the system in their homes.

Table 2. Overview of the homes of the subject

| Location                        | Completion year | Total floor area | Number of residents (With or without of children/elderly) | PV(kW) |
|---------------------------------|----------------|-----------------|----------------------------------------------------------|--------|
| A Midori city, Saitama prefecture | 2016           | 95㎡            | 3 people (children)                                      | 3.7    |
| B Midori city, Saitama prefecture | 2016           | 104㎡           | 3 people                                                 | 4      |
| C Kawagoe city, Saitama prefecture | 2016           | 119㎡           | 3 people                                                 | 5      |
| D Midori city, Saitama prefecture | 2017           | 105㎡           | 2 people                                                 | 3.9    |
| E Midori city, Saitama prefecture | 2017           | 98㎡            | 4 people (Children)                                      | 3.7    |
| F Midori city, Saitama prefecture | 2017           | 104㎡           | 4 people (Children)                                      | 4      |
| G Midori city, Saitama prefecture | 2017           | 98㎡            | 3 people                                                 | 3.71   |
| H Midori city, Saitama prefecture | 2017           | 99㎡            | 4 people (Children)                                      | 3.7    |
| J Midori city, Saitama prefecture | 2017           | 104㎡           | 3 people (Children)                                      | 3.7    |
| K Midori city, Saitama prefecture | 2007           | 50㎡            | 3 people                                                 |        |
| L Midori city, Saitama prefecture | 2006           | 105㎡           | 3 people (Children)                                      |        |
| M Midori city, Saitama prefecture | 2017           | 100㎡           | 4 people (Children)                                      | 4.2    |
| N Tokorozawa city, Saitama prefecture | 2014           | 110㎡           | 2 people                                                 |        |
| O Kamakura city, Kanagawa prefecture | 1999           | 140㎡           | 3 people (Elderly)                                      |        |
| P Tokorozawa city, Saitama prefecture | 2017           | 92㎡            | 3 people (Elderly)                                      | 4.4    |
| Q Musashino city, Tokyo Metropolitan | 2017           | 136㎡           | 4 people                                                 |        |
| R Hino city, Tokyo Metropolitan | 2008           | 105㎡           | 2 people (Elderly)                                      |        |
| S Matsuka city, Tokyo Metropolitan | 1975           | 88㎡            | 3 people                                                 |        |
| T Hashigui city, Tokyo Metropolitan | 2005           | 131㎡           | 2 people (Elderly)                                      |        |
| U Tsurugashima city, Saitama prefecture | 2015           | 118㎡           | 2 people (Elderly)                                      |        |

3.2. Overview of the questionnaire survey

We conducted a questionnaire survey to understand the extent to which subjects used the system as a reference and the extent to which they took action to regulate their environment and conserve energy. Research period of the survey is after summer experiment of each year. The survey was collected by mail and asked subjects about their awareness of the environment and energy conservation; how much they used the website, LED lamps, advice from the system, and weekly reports as a reference; and how much they engaged in environment-regulating and energy-conserving behaviors.

3.3. Schedule of the experiment

Table 3 shows the schedule of the experiment. The website was launched in August for all homes, regardless of when their system was installed. The real-time advice functionality suffered from delays in the summer of 2017 and was only activated in December due to technical issues that occurred during the winter as well. The creation and distribution of weekly reports began in 2018.

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4. Usage of the site
Figure 4 shows the frequency with which subjects browsed the site each month. In 2017-installed homes, the number of subjects that browsed the site at least once a week decreased in 2018. Meanwhile, in 2018-installed homes, the proportion of subjects that browsed the site at least once a week remained at about 75%, suggesting that they maintained their interest in the environmental information shown on the site. We also found that many of the subjects in 2017-installed homes only looked at the Home screen of the system, while the number of those from 2018-installed homes who browsed the environmental information changed by 20% every month. This suggests that interest in the environment was higher among the latter. In almost all homes, we found that subjects checked the LED indicators multiple times a day, which is more times than they used the site.

5. Usage of real-time advice
Figure 5 shows the aggregate result of the logs of the responses from the subjects to the advice. Overall, there was a high proportion of affirmative responses, such as “Already doing it” and “Will try it soon,” which suggests that subjects had a high need for advice. From the breakdown of the response logs and the number of times subjects are shown advice when they browse the site, we found that subjects in 2018-installed homes—who browsed the site more often—responded more frequently to advice.

6. Effect of distributing weekly environment reports
To determine the before-and-after effect of distributing the weekly environment reports, we chose two time periods with similar atmospheric conditions before and after distribution and compared electricity consumption and how comfortable subjects reported the effective temperature to be.
6.1. Confirming improvements in the tendency to conserve energy

Figure 6 shows electricity consumption for each home before and after the reports were distributed. Consumption decreased for about half of the residences A–K (2017-installed system), and almost all of the residences N–U (2018-installed system). When we compared the “high-consumption group” (above-average consumption before distributing the reports) with the “low-consumption group” (below-average consumption before distributing the reports) for each group of residences, we found that the tendency to conserve energy increased in the high-consumption group for both residence types (Figure 7).

Figure 6. Power consumption before and after distribution

Figure 7. Average change rate of electricity consumption before and after distribution

6.2. Confirming improvements in comfort

Figure 8 shows the average (indoor) operative temperature for each home before and after distributing the reports. The higher this value was before the reports, the more it decreased afterwards. When we compared the “comfortable group” (average operative temperature of ≤ 27 °C before the reports were distributed) with the “high-temperature group” (average operative temperature ≥ 27 °C before the reports were distributed) for each group of residences, we found that the comfort of the comfortable group had decreased that of the high-temperature group increased (Figure 9).

Roughly 70% of subjects in both groups responded that they referred to the reports on energy-saving and environment-regulating behaviors, and 95% of subjects—the greatest proportion—referred to the information on electricity.

Figure 8. Average operative temperature before and after distribution
6.3. The extent to which subjects referred to the reports

Figure 10 shows the results of a survey regarding the extent to which subjects referred to the reports. For attention (a), it can be seen that all those who received the report looked at them every time. Concerning items displayed (b), subjects referred to all of the information; the electricity graph, in particular, was used by 90%, the highest number of subjects. For each behavior (c), over 70% of subjects referred to the reports regarding energy-saving behavior, which is more than those who used them concerning environment-regulating behaviors. We could thus say that the weekly environment reports were used more to improve the conservation of energy than to improve comfort.
7. Conclusion
Upon checking for changes in behavior in subjects in a total of 21 households, as well as an improvement in their environment and energy conservation, we found that the LED indicators were used with a very high frequency and also led the subjects browse the site. In addition, subjects followed the real-time advice with a probability of more than 80%, suggesting that it was useful. The weekly environment reports distributed on printouts led to greater energy conservation in homes with a high electricity consumption. These results indicate that each part of the system—the site, LED indicators, real-time advice, and weekly environment reports—played a role in helping to promote environment-regulating and energy-conserving behavior.
Although this study is still a pilot project, if this system will become widespread in the future, it is expected that it will contribute to SDGs goal 3 by improving indoor environments, contribute to goals 7 and 13 by saving energy, and contribute to goal 11 by improving quality of life.

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