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Feedback on electricity usage for home energy management: A social experiment in a local village of cold region

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HIGHLIGHTS

- This paper purposed to reduce total electricity consumption of households in a cold area, Japan.
- We implemented an information provision system to install four households for one year.
- The system provided the information of electricity consumption 15 min interval via websites.
- We considered temperature effects to electricity demand and made a benchmark for evaluation.
- Consequently, a tendency of reduction of electricity consumption could be seen in two households.

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ABSTRACT

To mitigate global warming, it is essential for households to reduce CO_2 emissions. Saving electricity is one solution for the reduction. To promote this reduction, saving electricity by households should be considered because household consumption is growing rapidly. In this paper, we developed a system for metering electricity consumption and providing it to households as feedback on electricity usage. Previous studies on how to promote household energy savings found that feedback in real-time on electricity usage could be effective. Our system provided two types of information through web pages, (1) nearly real-time electricity consumption information, and (2) action lists for how to save energy. To test the effectiveness of these types of information, the system was installed in four households in an extremely cold district in Hokkaido, Japan for 378 days. During 30 days, data on electricity consumption was collected and stored. In the following month, a web page, which visualized nearly real-time electricity consumption, was opened to each household. After the experiment, an Internet-based questionnaire survey was conducted. The results obtained suggest that environmental awareness was an important aspect for inducing electricity saving behavior.

1. Introduction

To mitigate the phenomenon of global climate change, it is essential to reduce CO_2 emissions, which involves reducing electricity usage. Since domestic electricity consumption is rapidly increasing in Japan [1], energy efficiency measures have been used over a number of decades to reduce CO_2 emissions. We developed an Internet-based system for metering and visualization of electricity consumption, in order to promote reduction of household electricity consumption and elicit behavioral change for saving energy. Many studies that have utilized visualization systems for energy saving found that providing nearly real-time electricity consumption data, which is a feedback on electricity usage, and telling participants how to take actions for saving energy were effective [2]. We utilized feedback on electricity usage in our system. First, our system monitored nearly real-time electricity consumption using a metering system, which transferred data via the Internet to an online database. Second, we provided a web page, which provided feedback on electricity usage.

To test this system's effectiveness, we conducted an experiment with four households in a local village called Teshikaga-cho, in Hokkaido, Japan (Its town office is located at E144° 45′, N43° 48′). Temperatures in Teshikaga-cho from 2010 to 2012 were

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Table 1
Teshikaga-cho's average temperatures (°C) from 2010 to 2012 [3].

Degree	Winter			Interphase			Summer			Interphase		Winter
	January	February	March	April	May	June	July	August	September	October	November	December
2010	−6.4	−7.4	−3.5	1.8	7.3	15.2	18	21	15.8	8.9	2.8	−2.2
2011	−8.1	−6	−3.1	3.3	6.4	13.2	17.8	19.1	16.4	8.8	2.9	−5.8
2012	−8	−9.9	−4.2	2.6	8.4	11.7	17	18.9	18.3	9.7	2.9	−5.5

shown in Table 1. As illustrated in this table, Teshikaga-cho was a very cold resign and demand management in such a cold district had not been conducted in previous Japanese projects; now had its possibility been clarified. This was the originality of our experiment.

In the first phase, nearly real-time electricity consumption data were collected. In the second phase, a private web page was established for each household, showing the households' electricity consumption information. Following the experiment, we used the electricity consumption data and an Internet-based questionnaire survey to confirm the factors that affected the household's electricity saving behavior, with focus on environmental awareness.

2. Related works and our hypothesis

This section summarized relevant studies on the visualization of electricity consumption data. Previous studies can be divided into two categories.

The first category related to methods for collecting data on electricity usage by devices and Internet communication technology (ICT) [4–6]. The main purpose of these studies was to develop an efficient system for monitoring domestic electricity usage by using highly functional smart meters or smart taps, including collection and storage of data into a database. Another purpose was to develop a framework for combining the electricity network and the ICT network into a smart grid.

The other category was researches that employed visualization web pages or applications to change participant's behavior towards gaining energy savings. Another purpose of such studies was to determine which interventions could enhance energy-saving behaviors. Previous studies expecpredicted that gas and water energy would be used to a great extent because of their low environmental impacts [7,8]. After the introduction of the personal computer (PC) to households, many studies had moved from paper-based to Internet-based methods [9–11].

Our system focused on providing electricity consumption data over 15-min intervals; we provided the amounts of real-time electricity consumption and the number of W used per 15 min. This type of approach provided feedback on electricity usage [12].

3. System description

This section described the system used to monitor, collect, and visualize electricity consumption data.

3.1. Monitoring, collecting, and storing power consumption data

Our system used smart meters to collect nearly real-time data on household electricity consumption. Compared with standard electricity consumption meters, smart meters enable the optimization of customer demand and utility provider supply. The electricity usage information recorded by smart meters was typically used to calculate consumption charges; however, in this experiment, it was used to collect the data on electricity consumption and transmit this data via the Internet to a central database. Fig. 1 showed a smart meter installed in one household. Each smart meter was connected to a switchboard and gateway.

Fig. 1. Picture of a smart meter installed in a household.

In this system, the gateway was a small device that changed the communication protocol from the original protocol to a unified protocol, IEEE1888. The gateway was connected to a modem in the household to connect it with the Internet. We adopted the unified IEEE1888 network protocol for data acquisition via the Internet. IEEE1888 was an IEEE standard protocol for ubiquitous green community control with interoperability, e.g., unified data format, storage system, security system, and providing sample codes [13]. It already existed as a method for integrating ICT with smart meters [14,15]; however, our metering system had significant merits compared to them. Our metering system's novelty was in the use of the international standardized communication protocol, IEEE1888. This protocol has versatility for developing a HEMS (Home Energy Management System) and a BEMS (Building Energy Management System) systems. In this experiment, we used the same type of smart meters; however, various types might be used in other situations, as IEEE1888 unifies the data format even when different smart meters are used. Fig. 2 shows a system overview. The data is collected at 1-min intervals, stored, and accumulated. One of our previous works [16] showed that this system had high accuracy for collecting electricity data. In order to use this system, participants must have Internet access in their houses.

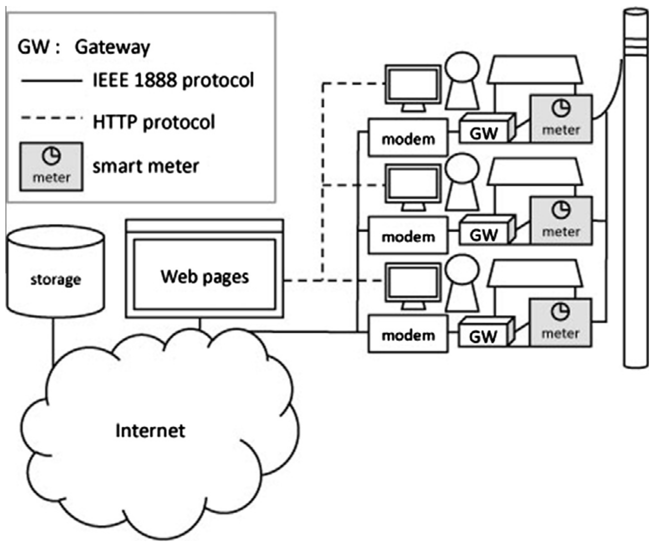

Fig. 2. Data collection and visualization system.

3.2. Visualization system

Our system used a web browser to show the participants their household electricity consumption. Fig. 3 showed a sample of web page. Each participant could access his or her personal web page via PCs, smart phones, or tablet devices. Fig. 4 showed an example of using such devices to view a web page.

The system was used in phase 2 (348 days). The detailed contents of each web page were described below. Table 2 shows the contents of the web page.

The web page provided information that helped households to take actions to achieve electricity savings (Table 3) [17]. These items also explained why particular actions affected energy savings, in order to enhance the households' understanding of the outcomes of their actions.

The participants could view the graph in a daily, weekly, or monthly format (Fig. 5), thereby enabling them to understand the patterns of their energy consumption. The participants could also see more detailed information on the graphs if they used a smart phone or tablet device with a touch-zooming facility (Fig. 6). From these functions, the participants could get their detailed electricity consumption status.

4. Methods

This section described the experimental methodology. The aim was to evaluate whether a target of feedback on electricity usage based on each household's characteristics could effectively incentivize electricity savings. Two measures were used for the evaluation: (1) a quantitative evaluation of the change in the amount of electricity consumption, and (2) a qualitative evaluation of the change of the household's consciousness and electricity saving behavior.

4.1. Participants

The experiment spanned approximately 12 months from 17th October 2011 to 31st October 2012 and included periods of an extremely cold winter and the summers from 2011 to 2012. From 1 October 2011, we began negotiating with the Teshikaga-cho town office to recruit participants, and identified four interested households; termed A–D. Household D was a control group. This household could only monitor its electricity consumption but, unlike the other participants, could not see the web page. Therefore, household D was not influenced by the visualization. Smart meters and gateways were installed in each household during the middle of October 2011.

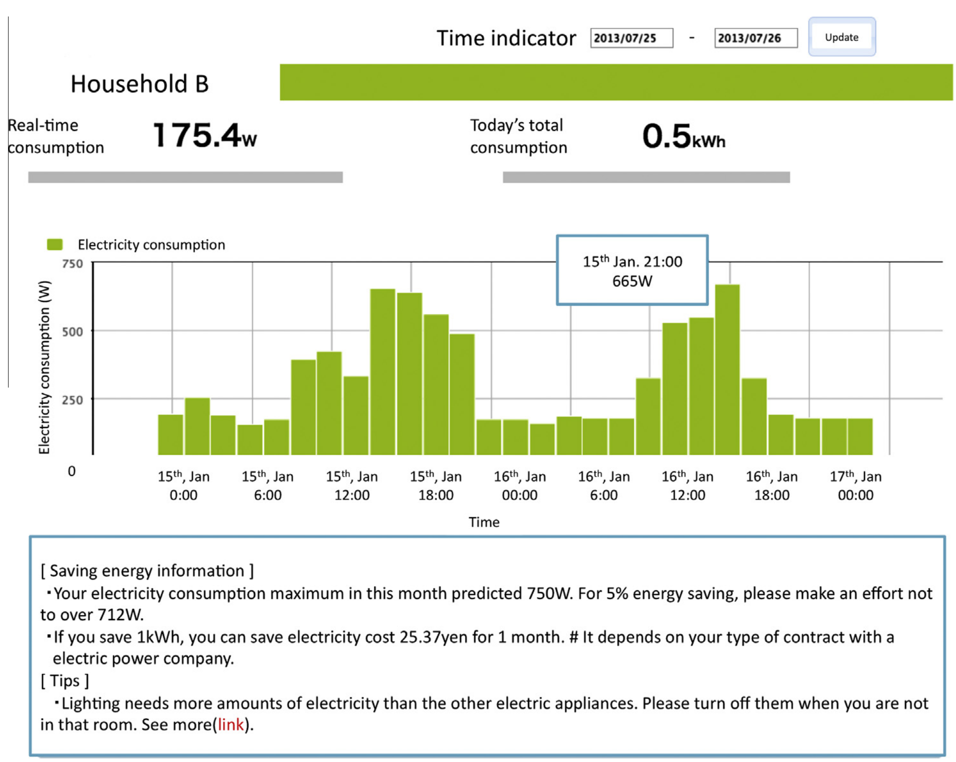

Fig. 3. Main screen of web page.

Fig. 4. Examples of using smart phones and tablets for viewing the web page.

Table 2
Contents of web page.

1	Amount of real-time electricity consumption (W)
2	Displaying electricity consumption as a graph, updated at 15-min. intervals
3	Integrating watt meter (W h)
4	Action items for saving energy

Table 4 showed the characteristics of the households. The heads of households A, C, and D were aged in their 40s, whereas the head of household B was in his 50s. We maintained contact with participants by phone, surface mail, and email. The average household size was 3.5 persons. Floor area was between 72 m^2 and 153 m^2 (the average was 106 m^2).

4.2. Study design

We conducted the experiment for 378 days between 17th October 2011 and 31st October 2012. During the first month, from 17th October to 16th November 2011 (phase 1), we monitored and collected electricity consumption data for each household at 1-min intervals. This established each household's electricity consumption pattern prior to the influence of visualization via the web page. Next, a web page was made available to the households for the period 17th November to 31st October 2012 (phase 2). At the same time, a first questionnaire was conducted via the Internet to establish the households' opinions regarding electricity consumption data, and it was administered to elicit the households' opinions after using our web page. Finally, a second questionnaire about the households' change of awareness and behavior was administered at end of phase 2 of the experiment. Table 5 showed the schedule and actions of the experiment.

4.3. Analysis

This subsection described how to evaluate the effects of feedback on electricity usage. First, we calculated a benchmark for residential electricity consumption per household. It was calculated using total daily residential electric demand in Hokkaido (31.8% of total demand, provided by Hokkaido Electric Power Co., Inc. [18]), which was divided by the number of households in 2011 or 2012 [19]. It was interesting to find that electricity consumption (kW h/day) had a strong relationship with outside temperature (Fig. 7 was created by using 2011–2012 actual electricity consumption and outside temperature data) as suggested elsewhere [20]. A strong relationship could be seen between temperature and electricity consumption; as temperatures dropped from 10° to −5° (October 2011 to March 2012), electricity usage increased; as temperature increased from 20° to 25° (July 2012 to August 2012), electricity usage declined, and then slowly increased due to the use of air conditioning; as temperatures were constant between 10° and 20°, electricity usage was not significantly influenced by temperature.

As had been determined, the relationship was non-linear, with the bottom of the consumption at around 10–15°. Therefore, the demand during winter and summer was high because of thermal demand (heating and cooling, respectively).

Hence, we estimated the electricity demand per household by using the temperature and the squared temperature (Fig. 8). Table 6 showed that the estimates for temperature and squared temperature were both statistically significant at the 1% level, and we obtained a reasonably high adjusted R^2 value. To create a model, we used 2011–2012s electricity consumption [19] and temperature data [3]. In the below analysis, we used the original data (not the predicted value) as the benchmark. To make the benchmark for the evaluation of the effects, we used Teshikaga-cho's temperatures (Table 1) [3].

Eq. (1) indicates the electricity demand estimation model:

$$Y = 14.5 - 0.3762 * (\text{Temperature}) + 0.01085 * (\text{Squared temperature}) \quad (1)$$

where Y donates 1 day's demand (kW) for 1 household in Hokkaido, and squared temperature denoted the squared temperature of the 1-day average temperature in Hokkaido.

Table 3
Action items for saving energy.

1	Lower daytime thermostat setting for air conditioner
2	Lower nighttime thermostat setting for air conditioner
3	Turn off air conditioner when not at home
4	Turn off air conditioner when leaving rooms
5	Lower setting for electric carpet
6	Defrost refrigerator
7	Try to use renewable energy e.g., photovoltaic
8	Try to use energy saving light bulbs
9	Turn off lights when leaving a room
10	Turn off TV when not watching it
11	Cover the lid of bidet toilet when not in use
12	Lower bidet toilet setting
13	Keep air conditioner filters clean
14	Try not to use energy during 9:00 am – 9:00 pm (peak time) too much
15	Know which electrical appliances consume much power, e.g., electric heaters, electric carpets, rice cookers, hot water dispensers, microwave ovens, electric griddles, toaster ovens, induction cooking, washing machines, dish washers, hair dryers, dry cleaning machines, vacuum cleaners, electric steam irons
16	Turn off and unplug PC when not using it
17	Try to choose energy saving electrical appliances
18	Try to unplug electrical appliances that have high energy use in the standby mode, e.g., hot-water heaters, DVD players, thermostat, bidet toilets, tuners of satellite broadcasting, microwave ovens

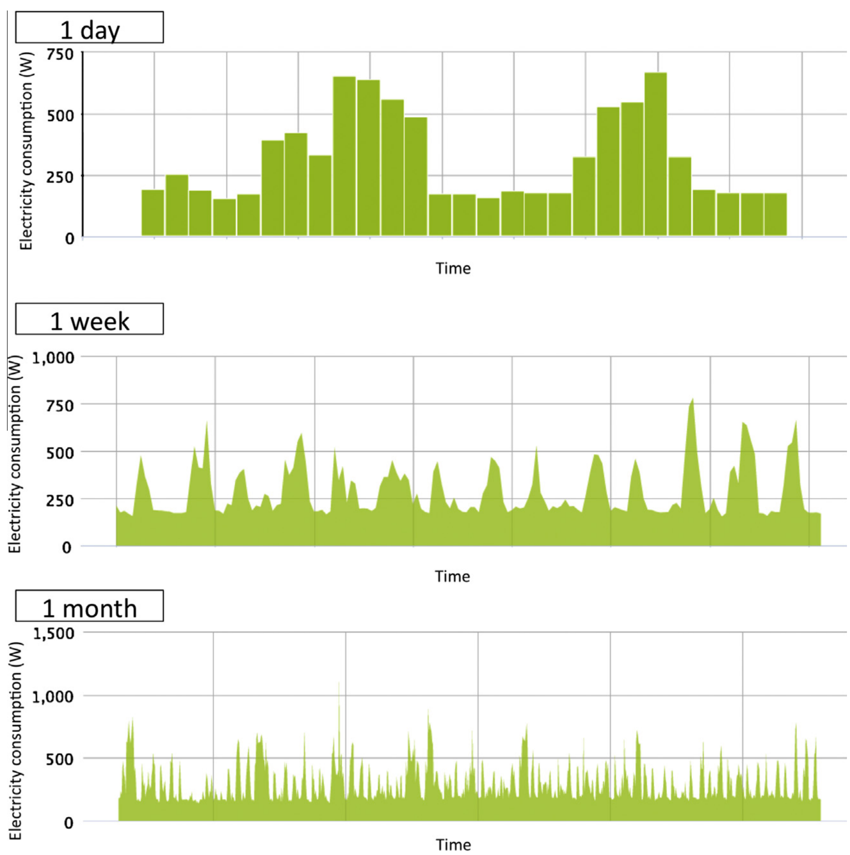

Fig. 5. Examples of graph patterns.

4.4. Results

In this subsection, the results of our experiment were described. We discussed the effect of visualized feedback on electricity consumption using quantitative and qualitative analyses.

4.4.1. Quantitative analysis

First, the quantitative analysis was conducted. As mentioned above, data from phase 1 was not influenced by the visualization of our system whereas data from phase 2 was influenced by the web pages. The consumption for each household during these two periods was compared to the benchmark value.

Fig. 9 showed the pattern of each household's electricity consumption during the experimental period. The thin, solid line was defined as the electricity consumption flow of household A. The dashed line was defined as the flow for household B. The double line was defined as the flow for household C. The dashed-dotted line was defined as the flow of household D (control). The bold, solid line was the above-explained benchmark. The consumption levels for households A and D were less than the benchmark before

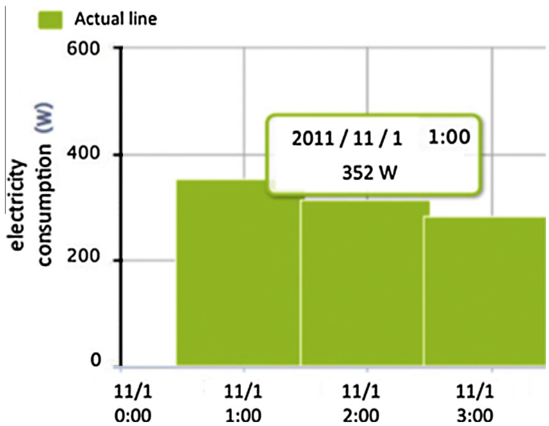

Fig. 6. Example of a zooming web page.

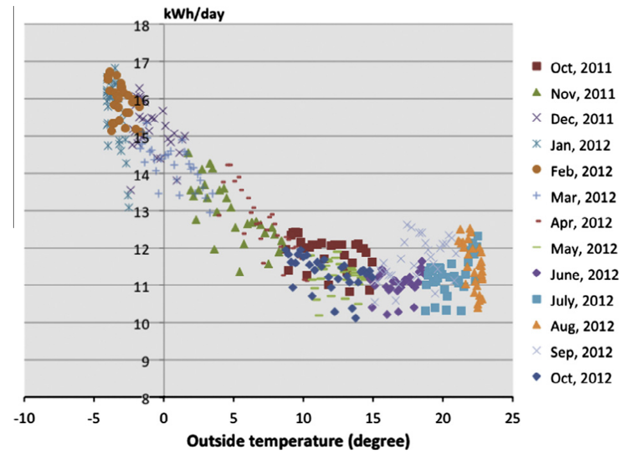

Fig. 7. Relationship between outside temperature and residential electricity consumption per household in Hokkaido.

Table 4
Characteristics of the households.

Household	Number of household members	Head of household	Floor space (m^2)
A	2	40s	72
B	5	50s	153
C	3	40s	143
D	4	40s	59

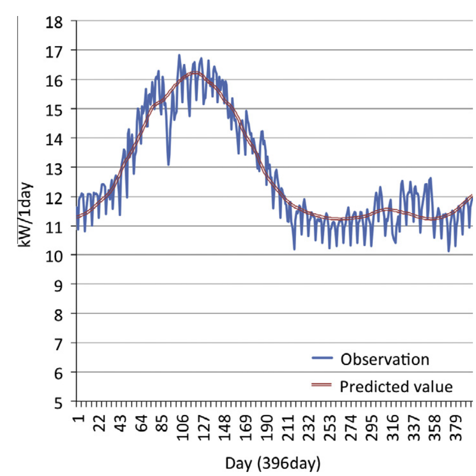

Fig. 8. Observed and predicted values of household electricity consumption in Hokkaido.

Table 5
Schedule and actions of the experiment.

Phase	Schedule	Actions
1	17th October to 16th November, 2011 (30 days)	• Start to monitor and collect energy consumption data
2	17th November to 31st October 2012 (353 days)	• Open web page • First questionnaire (From 17th November to 20th November, 2011) • Second questionnaire (From 1st November to 3rd November, 2012)

the demand-response experiment. Hence, we calculated the divergence of each household's consumption from the benchmark as (benchmark - household's consumption/benchmark) for each day, and the averages for phase 1 and phase 2 were shown in Table 7. This table showed that the values of the averaged divergences for households A and C were raised, which indicated saving electricity. However, the value for household B got worse. In the below analysis, we investigated the causes of such results.

Fig. 10 showed 24 h/378 days of electricity usage patterns for each household. The figure had a range of 0–24 h, as the *x*-axis is defined as the study period, and the *y*-axis iswas defined as 24 hours' electricity consumption data. White space in Fig. 10 showed losses during data collection (missing data).

4.4.1.1. Quantitative findings. *Household A*: This household's average electricity consumption was lower than that of an average household in Hokkaido. The data indicated that household A followed an energy aware lifestyle. In addition, they used renewable energy, e.g., photovoltaic panels and a floricultural hot spring. However, after the visualization, household A's electricity consumption was going down compared with the benchmark's angle of flow. Especially, the consumption was reduced, even in the summer period.

Household B: Household B's electricity consumption increased rapidly during the winter period. Therefore, we interviewed with household B and found that: (1) they used three fan heaters because of lower temperatures during phase 2 compared with previous years, and (2) one household member stayed at home during the daytime of phase 2. In particular, the three fan heaters were of an old type that were much less electricity efficient than newer appliances. In addition, the members of this household were not influenced by the visualization after the winter period. Their consumption pattern was much higher than the benchmark consumption pattern

Household C: Household C's amount of electricity consumption was significantly greater, particularly in the winter period. We also interviewed with household C and found that: (1) they introduced an all-electric system (no natural gas for hot water, cooking, heating/cooling) to their home, and (2) they installed a photovoltaic system. Therefore, their electricity consumption was high, and their consumption was low during the daytime (see Fig. 10's household B part).

Household D: Household D was the control household for comparison with the other households that had access to the visualization web page during the experiment. Household D's electricity consumption pattern showed similarity with the benchmark pattern. From household D's distribution map (Fig. 10), we could

Table 6
Parameter estimation results for the electricity demand estimation model.

Variables	Coef.	Std. error	*t*-Value
Intercept	14.50	0.0421	344
Temperature	−0.3762	0.00892	−42.2
Squared temperature	0.01085	0.000467	23.2
Adjusted R^2		0.901	
# of samples		397	

clearly see the relationship between temperature and electricity consumption.

Next, the results of behavior were described.

4.4.2. Qualitative analysis

Internet-based questionnaires were distributed to the households to elicit information about the changes in their awareness and actions during phases 2. Refs. [21,22] pointed out that cost merit and environmental awareness induced people's energy saving behavior. However, such factors may change from country to country. Therefore, we clarified the factors of Japan. The themes of the questionnaires were: (1) change of awareness about energy saving, and (2) changing behavior regarding energy saving. More detailed questions were shown in Tables 8 and 9. The web pages provided a list of action items with information on saving energy (see Table 3). The questionnaires asked each household whether they actually took actions, and responses were evaluated according to a five-point scale.

Before describing the results of this measure, we first defined the difference between "effectiveness" and "outcome." Effectiveness was defined as the possibility of making households changed their opinions and took practical actions to saving energy. Outcome was defined as an increase or decrease in energy consumption. The purpose of the study was to reduce electricity consumption; therefore, outcomes were defined as decreases in the amounts of energy consumed.

From the questionnaire survey, we found changes in both the households' awareness and actions. With regard to the change of awareness, households A and B had high scores of +4. Household A was already an energy-aware household; however, their awareness was further raised with our system because they could see

Table 7
Percentage of variance from the moving average between the households and the benchmark.

	Percentage of variance from the moving average			
	Household A	Household B	Household C	Household D
Before feedback	0.30249	0.48735	0.11884	0.34137
After feedback	0.40567	0.25959	0.18328	0.33598

real-time changes in their electricity consumption. This results suggested that visualization of consumption would be effective for households who were ecologically inclined, and would increase their motivation.

Regarding changes in behavior (see Table 10), households A, B, and C took actions to save energy. Households B and C stated that the list of action items was the most effective trigger for saving energy, because they were not aware of practical actions for saving energy before they used our system. Household A stated that the information provided about the influences of energy consumption on CO_2 emissions and global warming was the most effective motivator for energy saving, because they already knew how to take practical energy-saving actions. It was evident from their responses that providing suitable information to households about saving energy would be highly effective. Fig. 11 showed how each household changed their awareness and behavior. The findings were summarized below.

4.4.2.1. Questionnaire findings. Household A: From the questionnaire, higher environmental consciousness could be seen in household A. Moreover, they were already highly environmentally aware before the experiment, e.g., they were using photovoltaic panels and thermal energy in daily life. About the action change, a consciousness change could be seen in their desire to take more energy saving actions. However, they had already installed an efficient way to reduce their consumption from the beginning, via the utilization of renewable energy. Therefore, they took actions to achieve energy savings, and they were not strongly influenced by the amounts of energy consumption. They said that they could keep their motivation to take actions because they can see the results of their efforts by watching the web pages.

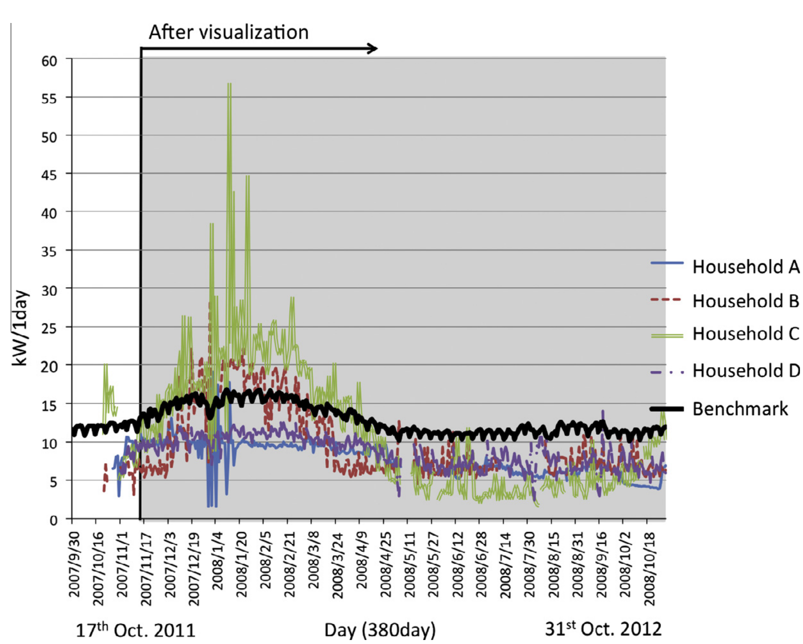

Fig. 9. Comparison of benchmark and collected consumption data for each household.

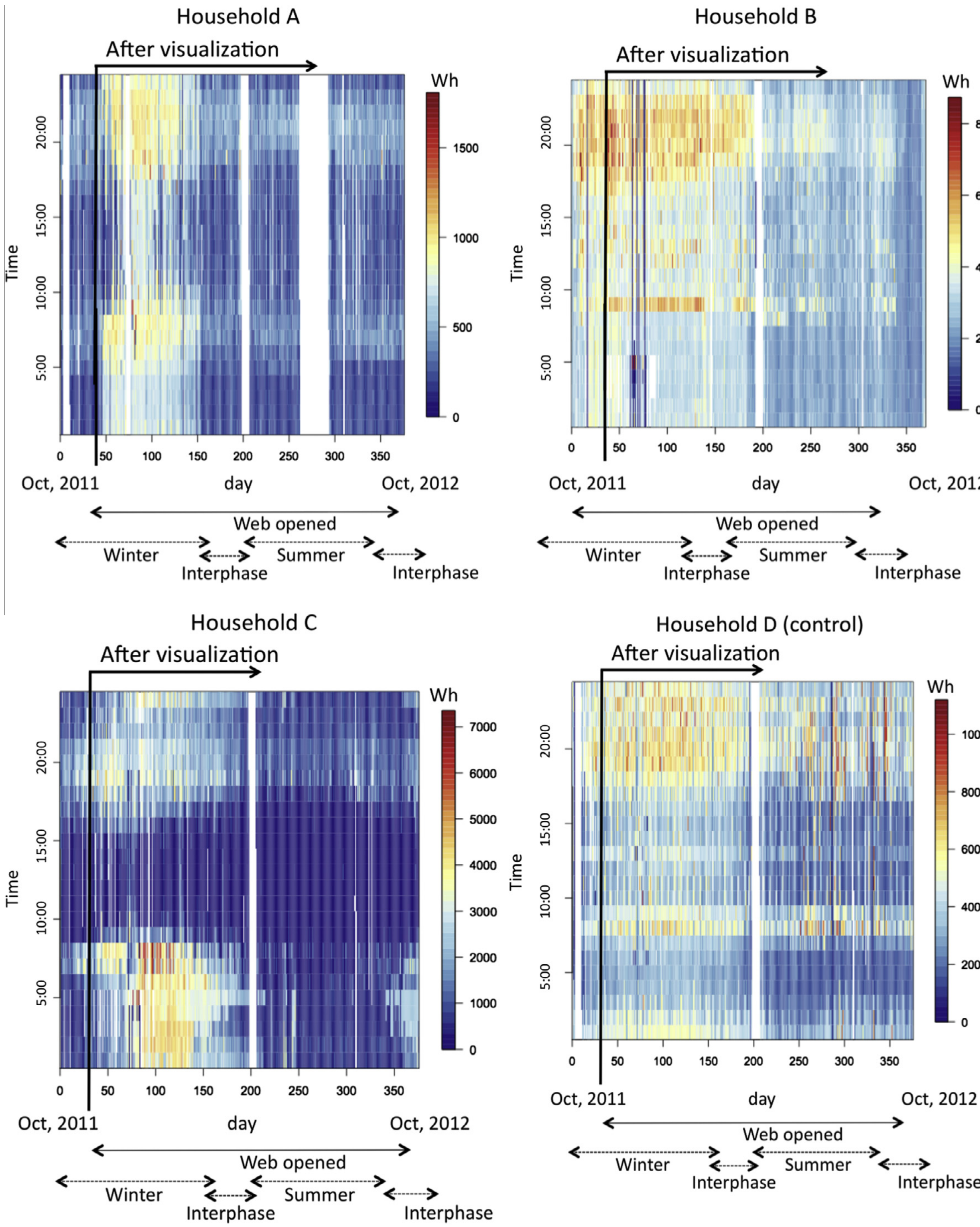

Fig. 10. Effects of feedback on electricity usage for each household.

Household B: They attempted to save energy; however, their circumstances changed during the experiment, e.g., (1) using high electricity consuming electric appliances during winter, and (2) a family member was unexpectedly at home during the day. After the winter period, we interviewed with this household, and then, they found that the cause for the high electricity consumption was usage of electric appliances. They said they would use affordable substitutes, if they could find such items. This perspective would be one of the effects of visualization of electricity usage and behavioral change. This household's electricity consumption pattern was changed by their living style, frequently including usage of electric appliances.

Household C: They changed their awareness and behaviors due to the visualization. However, they introduced the all-electric system to their household, and installed photovoltaic panels. They consumed high amounts of electricity for living, although they produced the electricity by themselves (the effects can be seen in Fig. 10; their daily electricity consumption was low, especially from April onwards). From the viewpoint of reducing CO_2, they did not use oil for heating. We should care about (1) considering the other action plans reducing electricity consumption for households that have introduced renewable energy, and (2) an evaluation of its CO_2 reduction effect.

Table 8
Questionnaire items about changes in awareness.

1. Did you become more aware about saving energy with this system?
2. Did you become more aware about saving energy with a target?

Table 9
Questionnaire items about changes in actions.

1. Did you take actions for saving energy with the help of the action list?
2. Did you take actions for saving energy based on the value of CO_2 emissions, e.g., how electricity consumption relates to increase or decrease in CO_2 emissions?
3. Did you take actions for saving energy with the help of the relationship between electricity consumption and global warming?

Table 10
Results of the questionnaires.

	Household	A Household B	Household C
Change of consciousness			
Start of the experiment	2	2	1
End of the experiment	4	4	3
Total	6	6	4
	Very good + 2/Good + 1/Average + 0/Poor-1/Very Poor-2		
Change of actions			
Start of the experiment	4	3	3
End of the experiment	6	5	6
Total	10	8	9

We did not ask household D about energy consciousness because they were the control group without access to the web page.

4.5. Discussion

Before starting the discussion about our experiment and each household, we explained the Hokkaido area's electricity situation. After the Fukushima crisis, the Hokkaido area also should have been seriously considered for energy saving because the Tomari Nuclear Power Plant, which covered about 40% of demand and was managed by Hokkaido Electric Power Company, Inc., was stopped from 23rd April to now (August 2013) [23]. For this reason, Hokkaido Electric Power Company proceeded to ask for 7% energy saving by all customers. Therefore, we considered that this action also influenced our experiment, e.g., household D (control group) also reduced their consumption. Comparing October 2011s with October 2012s consumption, 2 kW/month reduction could be seen. We should consider this to be the influence of mass-media.

Next, we disucssed the results of our measurements from the two measures of evaluation, e.g., (1) the change in the amount of energy consumption, and (2) the change in environmental awareness and actions for energy saving. We could test the efficiency of our visualization of electricity consumption data as feedback on electricity usage. From the quantitative results, only the feedback on electricity usage was not enough for energy saving because reductions in electricity consumption could not be seen from households A to D. However, we got data for a cold area's electricity consumption pattern. This should facilitate the design of new action plans for energy saving. From the questionnaire survey, we found that environmental awareness was important for motivating energy saving behavior. This result may support the importance of the long-run policy to raise people's environmental awareness, such as environmental education policy. Additionally, it was also very important to learn how to take actions for the reduction, and the actions would be different for each household condition.

5. Concluding remarks

In this paper, we collected electricity consumption data and developed a visualization system for energy saving for households, providing information on real-time electricity consumption and goal setting as feedback on electricity usage. To test this system's effectiveness, we conducted the experiment with four households for approximately 13 months in Teshikaga-cho, Hokkaido, which is a cold area in Japan.

We summarized our experiment's results by these two measures: (1) change in electricity consumption by each household (quantitative analysis), and (2) changes in environmental awareness and energy saving actions by households (qualitative analysis). First, the quantitative analysis showed two households' reduction of electricity consumption. Hence, we could determine the electricity consumption pattern of each household, e.g., the PV users' and the all-electric user's electricity consumption patterns in the 1-day and 1-month versions. Moreover, the benchmark's consumption pattern and household D's consumption pattern were similar. Therefore, this indicated that feedback on electricity usage by households affected them, even if not for reductions in consumption. Furthermore, there was a possibility that if our system provided effective information reflected by household characteristics; then more reductions would be expected. Second, the qualitative analysis showed the inner changes toward environmental awareness of households A–C. Ideally, their environmental awareness would be connected with reductions in electricity consumption; however, if they did not know how to reduce consumption, environmental awareness could not correspond to actual consumption changes. Educational information and customized information were necessary to enhance changes in their behavior.

As a next step, continuous data collection and high-level analytical methods are important. In future studies, we will collect

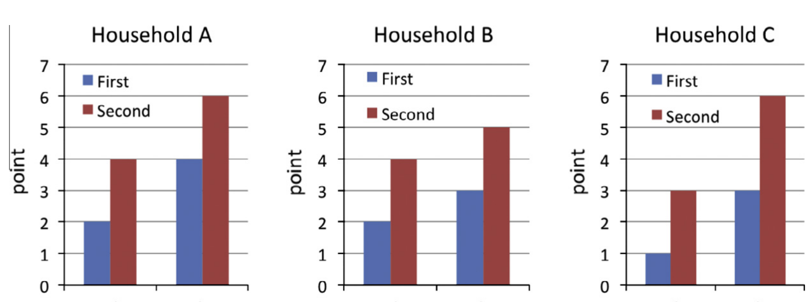

Fig. 11. Charts of the changes in participants' consciousness and actions by the experience.

electricity consumption data continuously over two years and consider seasonal variations. However, it is important to identify the participating households' characteristics and their living patterns. The present results demonstrate the differing characteristics of the four households. To analyze the effectiveness of visualized feedback on electricity usage, it is necessary to collect data from various households. Moreover, careful observation is required of how many times households access the web page and how long they remain logged-in. Such data will indicate the relationship between seeing nearly real-time electricity consumption and actually reducing electricity consumption.

Overcoming these types of limitations will enable future studies to employ more advanced analytical methods. In addition, we will also obtain electricity consumption data for the city to scale up our analysis in the near future.

Three challenges are identified for future research.

(1) Baseline evaluation can be improved to consider dynamic household circumstances as well as temperature sensitivity.
(2) We found that each household had a pattern of electricity use. Future studies will establish household clusters, and provide more personalized and specific information to each cluster.
(3) To acquire information on detailed patterns of electricity use, it is necessary to develop a database that detects the use of specific electrical household appliances and differentiates them from total electricity consumption.

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