Applied Energy 106 (2013) 314–320

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy consumption feedback devices' impact evaluation on domestic energy use

Iana Vassileva [a,*], Erik Dahlquist [a], Fredrik Wallin [a], Javier Campillo [a,b]

[a] School of Sustainable Development of Society and Technology, Mälardalen Univeristy, P.O. Box 883, SE-721 23 Västerås, Sweden
[b] Facultad de Ingeniería, Universidad Tecnológica de Bolívar, CO-160002 Cartagena, Colombia

HIGHLIGHTS

- Effects of SMS, display, letters and TV feedback on consumption were evaluated.
- Consumers' opinion and feedback preferences were analyzed through questionnaires.
- Changes in consumption patterns explained by introduction of visualization method.
- In-home displays and TV caused the major reductions.
- Information relevant to the users should be included in feedback.

ARTICLE INFO

Article history:
Received 19 September 2012
Received in revised form 15 December 2012
Accepted 19 January 2013
Available online 27 February 2013

Keywords:
Feedback
Domestic consumption
Electricity
Visualization
Electricity consumers
Consumers' preferences

ABSTRACT

Household energy accounts for one of the major contributors to the countries energy balances. It has been shown, that an effective way to achieve energy saving in that sector, is by providing consumers with information and feedback. This measure increases home inhabitants' awareness that leads to behavioral changes, and could help reduce energy consumption between 15% and 25% in some cases. Inhabitants' energy use awareness is also crucial for the success of demand response programs; one of the most important features of smart-grid adoption for the current and upcoming smart cities.

The effects of different feedback strategies and information devices in households located in different cities in Sweden have been evaluated in this paper, since the impact on users' behavior of this feedback information vary depending on the way it is provided.

Mobile text messages (SMSs) and digital displays placed in the building's common areas did not cause any noticeable behavioral changes, while the use of a TV channel and personal in-home displays were the most popular devices amongst households with high incomes.

This paper concluded that even though feedback helped reduce domestic energy consumption and induce behavioral changes, it only reaches the consumers interested in it. It is important therefore to provide customized information to the consumer and select precise feedback tools for specific household groups. Special attention should be paid to increasing the energy consumption awareness in households with low income levels.

1. Introduction

Europe consumed 3170 TW h of electricity in 2008; 54% from burning fossil fuels, but what is more important, most of these fuels were imported (83.5% oil and 64.2% gas), increasing the supply dependency of the European Union [1]. Households alone, account for more than a quarter of the EU's total energy consumption. If all the office buildings' energy consumption is included, the building sector accounts for 40% of the total energy consumption in the Union [2].

In Sweden, the final use of electricity in 2009 reached 125 TW h of which the residential and services sector (formed by residential and commercial premises, holiday homes and land use) used 73 TW h, almost 60% of the total consumption. The total energy use in the sector was 149 TW h (residential buildings and commercial premises accounting for 87%) or 39% of Sweden's total final energy use [3].

Increasing domestic energy demand is transforming the households sector into one of the major contributors to the country's energy balances. Some forecasts show that in the near future,

* Corresponding author. Tel.: +46 21 10 73 68; fax: +46 21 10 13 70.
E-mail address: iana.vassileva@mdh.se (I. Vassileva).

0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2013.01.059

domestic energy consumption will exceed 40% of the total yearly consumption [4].

Large consumption differences found in buildings with similar characteristics (same number of occupants, same buildings' properties, similar income levels, etc.) confirm the strong influence that occupants' behavior has on the energy use [5].

Despite some prognostics showing stabilized levels of electricity consumption due to increased efficiency in domestic appliances, consumption is growing due to the intensive use of appliances together with a population on the rise [6].

In order to reduce users' impact on electricity demand, several strategies have been developed over time. Three of the main methods are mentioned by Wood and Newborough [7]: replacing the existing housing stock with low-energy buildings, promote use of high-efficiency domestic equipment and finally, promote energy-conscious behavior among the consumers. While the first two would be both time and money intensive, changes in behavioral patterns can save energy without additional investment in infrastructure with immediate results [8].

It is therefore essential to focus most of the efforts into increasing consumers' energy awareness and knowledge in order to achieve positive behavioral changes. Different research shows that users reduce their consumption due to energy-use information and feedback [9–11]. The effectiveness of the feedback would depend on the way it is delivered (web based, display, etc.) and the information it contains. It can be hard for some consumers to connect their behavior and everyday activities to the actual electricity consumption [12].

The main goal of this paper is to determine the effects of different visualization methods for energy consumption and the possible changes made in occupants energy–consumption awareness (through changes in the consumption patterns).

2. Background

Several researchers have tested different strategies to induce behavioral changes and to increase their energy consumption awareness on household users. Research has been directed towards evaluating those strategies and to establish the factors determining domestic energy consumption. In a recent study performed by the University of Gothenburg, 4000 Swedish households were selected by the Society, Opinion and Media Institute for studying patters of energy savings [13]. The most prominent socio-economic factors affecting energy consumption were found to be: age, housing type and household income. Also environment-related attitudes were found to have weaker effects on saving energy in owner-occupied detached houses. Homeowners seemed to react better to economic incentives. Households with higher incomes and living in non-detached houses (and apartments) were more sensitive to environmental attitudes. The study recommends that policy measures should be tailored to fit household preferences depending on income and housing forms.

Income is a factor which is also pointed out as one of the main factors affecting electricity consumption by other authors [5,14]. Moreover, consumers' income, dependent usually on their age also influences consumers' energy visualization preferences (the elderly consumers, with low income usually preferred letters, while those in their middle age usually with higher incomes preferred web sites) [15].

Ek and Söderholm, analyzed 564 questionnaires in Sweden, concluding that price incentives, information and environmental moral concerns are essential to promote less electricity use [16].

Sardianou analyzed the energy conservation in 500 Greek households using face-to-face interviews with one adult from each household [17]. The energy-saver consumer was characterized by having a high income, being the owner of the house and also being a member of an extended family core. On the other hand, the number of rooms, size of the dwelling, the sex, educational level and marital status could not be considered as predictors of energy conserving behavior.

Whether the consumers own the house or not was found by Palm to influence the largest part of their energy consumption [18].

Ndiaye and Gabriel, conducted a similar study in Canada including 221 phone surveys and 1-year electricity consumption data [19]. Amongst the 60 variables that were included in their principal component analysis, the number of occupants, the home ownership and the vocational period were selected as the main energy consumption predictors.

A number of researchers point out that behavior (as the action taken by the households in their use of energy at home) plays a major role in determining energy consumption [20–23]. It seems therefore logical to target different behavioral aspects when attempting to increase energy awareness and savings. This could be mainly achieved by providing feedback and information. These tools would also make the electricity more visible, especially important in countries like Sweden, where until recent years electricity was included in the rent. Different studies show that the way feedback is provided determines to a certain degree the saving achieved. Direct feedback (in-home displays) for instance, could save up to 15% electricity, while indirect feedback (bills) would only achieve reductions of 10% [10]. Consumption information provided through a web site reached saving by up to 18% however only within the group of households that had visited the web site frequently [15].

Consumers' preferences on the way of receiving feedback and information and their behavior and characteristics however have not been considered in most of the cases when utilities design their energy efficiency and awareness plans Table 1.

3. Methodology

The information gathered from the occupants was related to socio-demographic variables, lifestyles, feedback preferences and their thoughts on the provided energy consumption devices. Questionnaires were chosen to collect such information due to compatibility and comparability with previous research where the effects of a web based feedback were evaluated [24]. Four different parts could be distinguished in the questionnaires, some of them common to all households groups. At first, questions focused on information about the occupants (level of education, monthly income, how many people live in the apartment, how many weeks the occupants spent away from their home and age of the respondents

Table 1
Description of all household groups.

	Location	Households total/responded	Visualization device	Period of collected consumption data
Group I	Gothenburg	80/28	In-home display; SMS; letter	January 2011–May 2012
Group II	Malmö	28/10	Common display	June 2011–February 2012
Group III	Hägersten	81/44	In-home display	March 2012–May 2012
Group IV	Sollentuna	70/29	TV-channel	December 2011–June 2012

among others). The second set of questions, also common to all questionnaires, contains the frequency of use and year of purchase of some domestic appliances (dishwasher, washing machine, fridge, oven, computer, TV, electric heaters, etc.). The third part was composed by questions related to energy related behavior, knowledge and awareness (how to save energy, occupants' interest in energy related topics, types of light bulbs used at home, use of standby, and others). Also the respondents' preferences when it comes to tools for energy consumption feedback were included in all the households groups. It is important to notice that only in group I, households were asked to choose the feedback method they preferred previous to providing them with the corresponding device; all the rest of the households' preferences were collected through the questionnaires after using the chosen feedback devices. Some extra questions regarding the specific energy visualization devices (what do the respondents think about the information provided, the colors used, the size, etc.).

3.1. Households description

Four groups of households were included in this study. In the beginning, questionnaires were sent out to 80 households located in Gothenburg (group I). The occupants of the households in that location have a generally low income and a foreign background. After two reminders, the response rate achieved was of 35% (28 households). The tenants living in these apartments started paying for their electricity consumption in January, 2011. Prior to this it had been included in their monthly rent.

The second group (group II), located in the city of Malmö, in the south of Sweden and composed by a total of 24 apartments reached a response rate of 41%. These households were characterized for having a generally low income and were located in a building with three other entrances. Their hot water consumption was compared with apartments located in the other entrances of the building. These households were also paying for their electricity consumption. Individual payment for hot and cold water from the tap was planned to be introduced in the near future.

The third group (group III) consisted of 81 apartments located in Hägersten (in the proximities of Stockholm). These apartments were characterized by high income and newly built buildings, with new kitchen appliances. The response rate reached there was 54% (44 apartments) after one reminder. This group of apartments was of interest to see the short term effects of visualization devices on the overall households' consumption.

The last group of households (group IV) was located in Sollentuna, a municipality in Stockholm County. As well as group III, households in this group were characterized by high income. After one reminder, the response rate reached was 46% (29 out of 70 households).

Consumers from both groups III and IV are paying for their electricity consumption and it has never been included in their monthly rent.

With the last informative letters that accompanied the reminders, cinema tickets (2 per household) were promised to all households that would answer the questionnaire. Tickets were sent out to the households that answered the questionnaire the first time as well.

3.2. Description of the feedback tools

In the case of the 80 apartments located in Gothenburg (group I), the consumers were first asked through questionnaires, about the type of device they would prefer for receiving electricity consumption information. Furthermore, in-home displays (as seen in Fig. 1), SMS, and letters (as seen in Fig. 2) were used to deliver current consumption and comparisons to similar households or previous day or months. From all the households that responded, 3 were given displays and 4 SMS. 40 letters were sent to some of the other households. The letters were sent in week 8 and contained the corresponding apartment's consumption for the first 6 weeks of 2012. During the same period the SMS service was used weekly for a period of 2 months showing the consumption for the corresponding week.

In order to evaluate the effects of energy information feedback for other sources of domestic energy, a touch screen display showing the tap hot water consumption was placed in the lobby of the study building located in the city of Malmö (group II). The installation of the display took place in October, 2011. The information shown was the current tap hot water consumed by the apartments situated in that building (Fig. 3), a comparison to the average consumed by the other 3 stairwells (forming part of the complex), and the hot water consumed by the apartments the week before. The

Fig. 1. In-home display given to households from group II (Gothenburg).

You have used this much energy in your apartment in 2012:

Your use of electricity in 2012 (kWh)	**Average use on Fänkålsgatan 10 – 13 (kWh):**
Week 06: 147,39	Week 06: 64,49
Week 05: 135,11	Week 05: 60,88
Week 04: 95,73	Week 04: 60,05
Week 03: 105,12	Week 03: 69,85
Week 02: 118,38	Week 02: 54,02
Week 01: 133,25	Week 01: 62,00

YOUR ENERGY USE IS 98 % HIGHER THAN OTHER PARTICIPANTS IN THE PROJECT

Fig. 2. Part of the letter sent to participants from group I where their weekly electricity consumption is compared to the average consumption of other households in the same building.

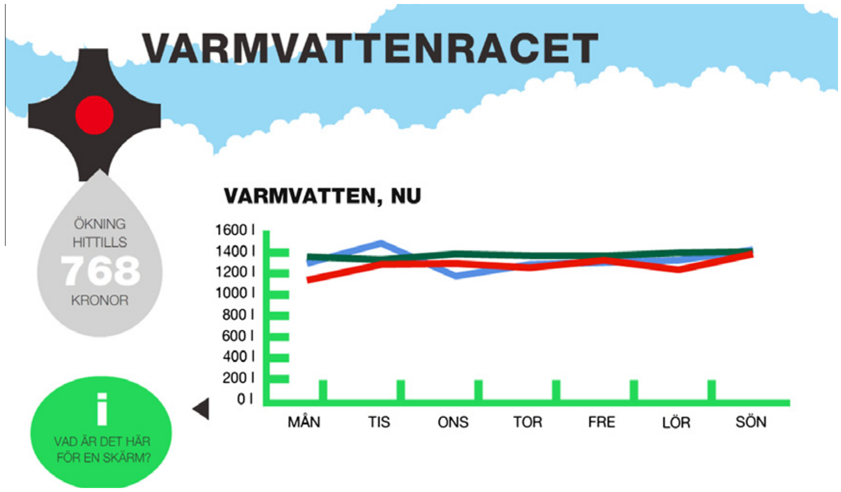

Fig. 3. Hot water consumption information provided with a display interface.

users were also able to see the cost (in Swedish krona) accumulated since the installation of the display. Several meetings and energy related information were provided for the tenants before and after the installation of the display. Additionally, all households from group II received a "cardboard spinner" which showed the electricity used by some appliances and the standby consumption for different year periods (1–50 years). Different measures and tips on saving electricity and hot water were provided to the tenants in form of letters and personal meetings. Their electricity consumption was also analyzed and compared to the other groups.

Another group of households, located in Hägersten, Stockholm (group III) were given the possibility to visualize their electricity consumption through an in-home display located inside their homes (an image of the display can be seen in Fig. 4). All the apartments were equipped with in-home displays mounted on the wall in the hallway. The apartments were located in 4 different stairwells of one building in which the fifth one had no display and was therefore used as a control group. The colors and intensity of the digital display changed according the electricity consumption levels.

The last group (group IV) received their electricity consumption information on their TVs (Fig. 5). A special channel created by the local digital TV provider displayed the individual apartment's electricity consumption together with traffic and weather information. All households had access to the channel through login details sent to them by the local digital TV provider. The service started in March 2012, the electricity use of the apartment being the feature that consumers were most interested in. The real-time use of electricity and that of the past 7 days was displayed on the TV screen, whilst users could also set their own consumption targets.

It is important to note that in this study electricity consumption was not affected by outdoor temperature since all the household groups were connected to the district heating network where water temperature is adjusted automatically according to weather conditions. Electricity was thus mainly used for lighting and domestic activities.

4. Results and discussion

The average incomes of the different households have been analyzed and range between 18,500 SEK/month (approximately 2140 €) in group I and 56,429 SEK/month (approximately 6523 €) in group III (Fig. 6). Results from previous research show a strong correlation between the households' average income and their electricity consumption, the higher the income the higher the consumption [15]. This could be applied to most of the groups analyzed in this paper. However, it could also be expected that consumption of group III would be higher than or at least as high as the one of group IV (Fig. 7). This is however not the case. The fact that group III has lower consumption than that of group IV could be due to the occupants of the apartments from this group still moving in and not having their appliances fully installed; also the consumption values do not include all winter months (since the first occupants only started moving in in January, 2012); one last explanation is a low consumption due to the effect of the display.

Fig. 4. In-home display used in households in group III.

When it comes to the electricity consumption trends of the different groups, households from group II had the lowest consumption levels even if the buildings and most of the electrical appliances were over 5 years old. However, consumers living in those apartments proved to be the most interested in energy related questions and tried the hardest to use their appliances and lights responsibly, which could explain the low consumption.

When analyzed individually, no significant changes in the consumption of apartments that received information via SMS and via the in-home display (group I) were found when compared to the same periods of the year before (Fig. 8a and b). The energy consumption increased in 2012 in comparison to 2011 for the apartments that got SMS and hot water displays. The large difference in the consumption levels of apartment 4 are probably due to different tenants living in the apartment in 2011.

On the other hand, if considering the global trend of group I, since individual meters were installed in 2010 and occupants started being charged for their consumption in January 2011, levels dropped by almost 6% with respect to previous years.

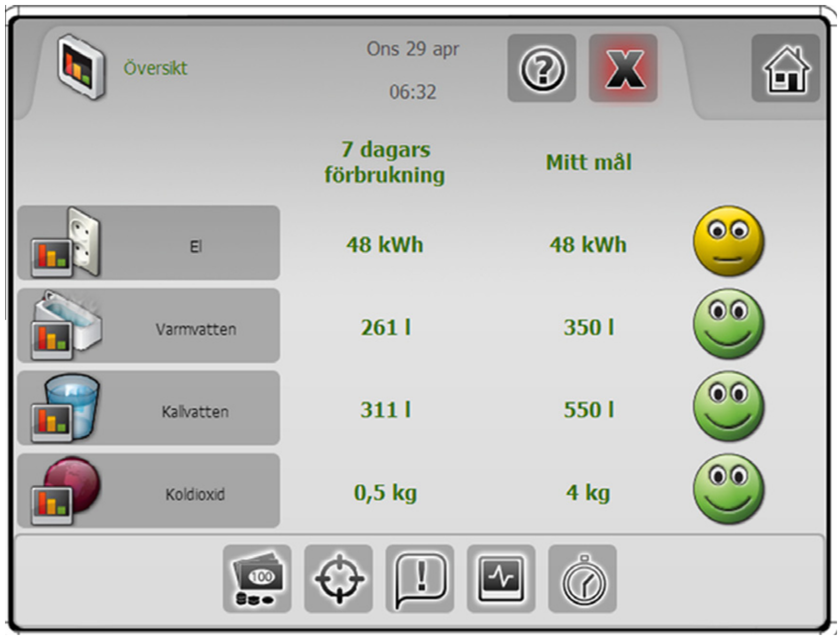

Fig. 5. TV-channel showing the energy consumption (for the last 7 days in this case, and individual targets) in the apartments of group IV [25].

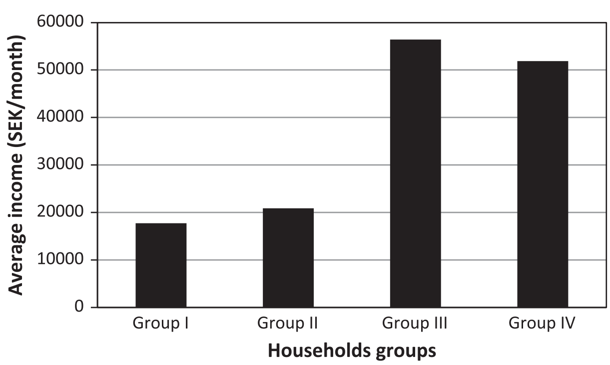

Fig. 6. Average monthly income per household for the different groups.

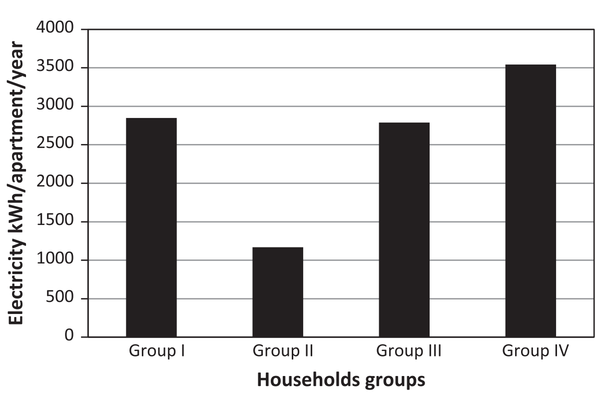

Fig. 7. Electricity consumption per apartment and year of the different apartment groups.

For group II the accumulated consumption was analyzed during 4-months before and 5-months after installing the common display. This showed a reduction in over 10% in the average monthly consumption after the common-display was installed (Fig. 9). These findings show that common-feedback might have a positive impact on consumption reduction on an aggregated level, the impacts on individual users, however, could not be determined given the limitations of the metering system used. This will be taken into account for future research work in order to understand the impact of aggregated-level feedback on both an individual and collective basis.

Apartments from group III have also been further studied in detail. Divided into the different stairwells, their consumption was compared to apartments comprising stairwell 1 which were not equipped with any visualization tool.

The occupants' ways of perceiving the information presented through the in-home displays was collected through the questionnaires. It was found that 34% of the respondents liked the display from the moment they moved into the apartment. 47% answered that they were looking at the display quite often while 19% of the respondents never consulted it. When comparing the levels of understanding of the information presented in the displays (as seen in Fig. 10) to the consumption levels reached by the different stairwells (Fig. 11), it can be observed that apartments located in stairwell 3 had the lowest consumption and were the ones that found the displays easiest to understand.

Also 10 of the total 21 apartments in stairwell 3 answered that they check their display very often and it also has the highest response rate when compared to the rest: 67%.

The differing impact that the displays had on the occupants can be due to the information and presentation made to them when they moved in. Different real estate agents introduced the displays and their functionalities to the new buyers and therefore, could have affected their acceptance and behavior. The initial low consumption of apartments (as seen in Fig. 11) from stairwell 5 is due to the owners moving in on different dates.

The energy information provided through the TV channel used in group IV proved to be the most used by the occupants. The highest consumption peaks observed in Fig. 12, between weeks 16 and 19 could be explained by the occupants testing the electricity consumption of their appliances and therefore consumed more than usual. Week 15 had an extra holiday day which was spent at home by some of the occupants. Of all the features provided through the TV channel, 39% of the respondents found that the energy information was the most interesting. Furthermore 36% had set their own

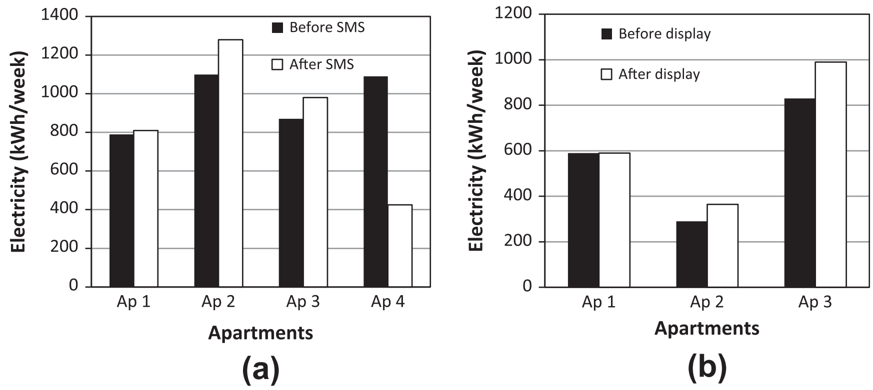

Fig. 8. Electricity consumption of apartments with (a) SMS (weeks 9–17 in 2011 without SMS; and in 2012 with SMS); (b) display (weeks 9–17 in 2011 before in-home display; and in 2012 with in-home display).

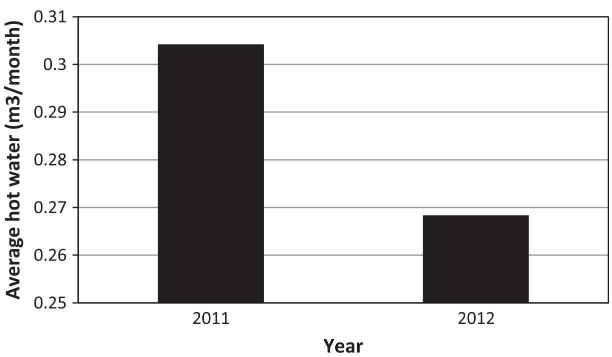

Fig. 9. Average monthly tap-hot water consumption for the households before and after the installation of a common display.

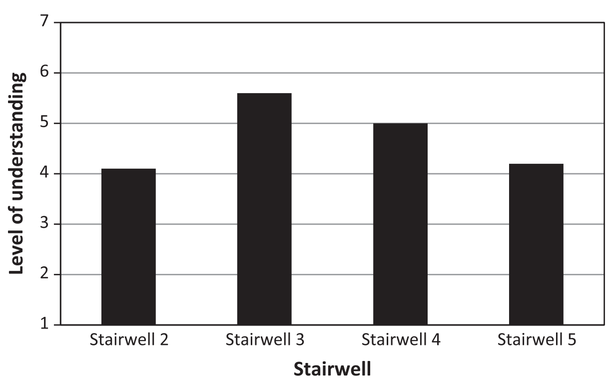

Fig. 10. Level of understanding of the display by the different apartments divided into stairwells (1 = very difficult to understand; 7 = very easy to understand).

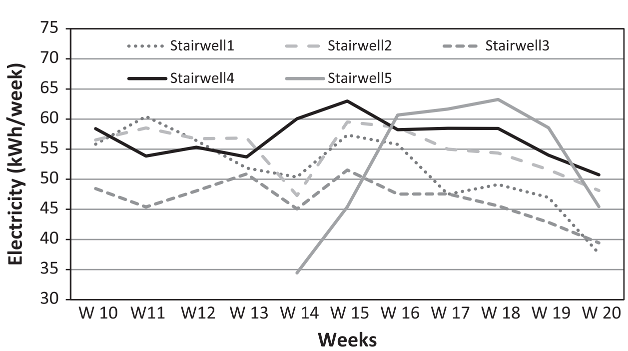

Fig. 11. Electricity consumption per week and stairwell (year 2012).

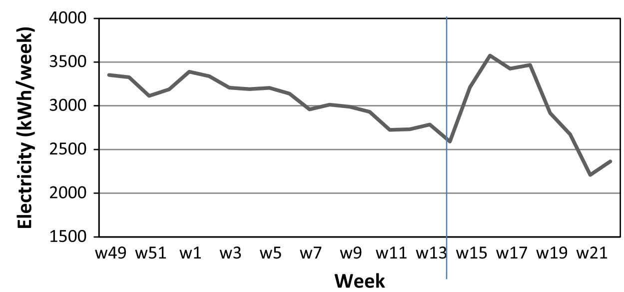

Fig. 12. Electricity consumption per week for apartments from Group IV. Vertical line marks the introduction of the TV-channel.

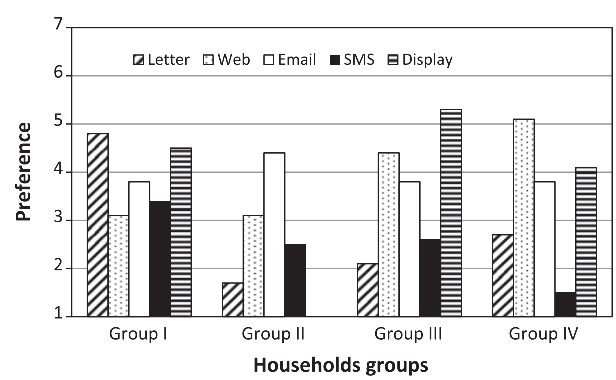

Fig. 13. Preferred visualization devices by the different household groups (7 = most preferred; 1 = least preferred).

consumption goal which is considered as one of the most effective strategies for saving energy and changing consumers' behavior.

The consumers were also asked to grade different types of visualization tools according to their preference (Fig. 13).

The results presented in Fig. 13 support the findings described in previous studies that feedback should be provided based on the consumers' preferences in order to achieve the expected results [26]. Some of the occupants' characteristics have also been found to play an important role when it comes to choosing a visualization tool. Households with high income usually prefer web sites or in-home displays [26] which in this case match households from groups III and IV.

5. Conclusions

This paper presents the influence of several visualization devices (common display, in-home display, SMS and TV channel) on domestic energy consumption.

Keeping consumers interested in energy related questions, and increase their awareness whilst creating long-lasting behavioral changes is a task that requires data management that results in providing feedback information that is specifically adapted to the households' characteristics in order to make it relevant for end users. Consumers' preferences should be taken into account when choosing the method for consumption information delivery. Additionally, it is important to identify households with larger savings potential during the early stages of these types of studies. For instance, in the present work, households from group II had the lowest consumption of all the groups, and consequently, the lowest potential for improved reduction. The use of energy information feedback devices in groups of households where consumption is already low (such as the ones where common and in-home display, SMS and letter were used), might in some cases, cause the opposite effect: when realizing that they consume less, occupants give less importance to their behavior impact on electricity consumption.

The TV channel used in the present study, rose great interest amongst consumers who were especially interested in the energy consumption feedback provided together with other types of information and could be an effective way of providing feedback. Another advantage is that it is also a good way to make consumers learn more about the consumption of their appliances, in the same way as the in-home displays would. However, only people interested in their energy consumption would go to the specific channel while the in-home displays are easier to observe (especially when located in central locations inside the household-hall, kitchen, etc.).

Different methodological approaches are currently being evaluated in order to study the long term effects of the different visualization devices used in this study.

Acknowledgements

The authors are thankful to the Swedish Energy Agency for the financial support to the research project "Energy in mind". We also thank all the partners in the "Energy in mind" project: Sustainable Innovation, Logica, Riksbyggen, Göteborg Energi, Maingate, JM.

References

[1] European Commission Statistics. Eurostats. <http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home> [01.06.12].
[2] European Commission. Low Energy Buildings in Europe: Current State of Play, Definitions and Best Practice; 2009 <http://ec.europa.eu/energy/efficiency/doc/buildings/info_note.pdf> [20.06.11).
[3] Swedish Energy Agency, Energiläget; 2007 [in Swedish].
[4] US Department of energy, 2008 buildings energy data book, Tech. rep., buildings technologies program energy efficiency and, renewable energy; 2009.
[5] Vassileva I, Dahlquist E, Wallin F. Analytical comparison between electricity consumption and behavioral characteristics of Swedish households in rented apartments. Appl Energy 2012;90:182–8.
[6] Statistics Sweden; <http://www.scb.se/Pages/TableAndChart____25896.aspx> (2012-09-12).
[7] Wood G, Newborough M. Dynamic energy–consumption indicators for domestic appliances: environment, behavior and design. Energy Build 2003;35:821–41.
[8] Ouyang J, Hokao K. Energy-saving potential by improving occupants' behavior in urban residential sector in Hangzhou City. China Energy Build 2009;41:711–20.
[9] de Almeida, Fonseca P, Schlomann B, Feilberg N. Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations. Energy Build 2011;43:1884–94.
[10] Darby S. The effectiveness of feedback on energy consumption. Oxford, United Kingdom. <http://www.eci.ox.ac.uk/research/energy/downloads/smart-metering-report.pdf> [29.06.12].
[11] Blom I, Itard L, Arjen M. Environmental impact of building-related and user-related energy consumption in dwellings. Build Environ 2011;46:1657–69.
[12] Ellegård K, Palm J. Visualizing energy consumption activities as a tool for making everyday life more sustainable. Appl Energy 2011;88:1920–6.
[13] Martinsson J, Lundqvist LJ, Sundström A. Energy saving in Swedish households. The (relative) importance of environmental attitudes. Energy Policy 2011;39:5182–91.
[14] Cayla J-M, Maizi N, Marchand C. The role of income in energy consumption behavior: evidence from French households data. Energy policy 2011. http://dx.doi.org/10.1016/j.enpol.2011.09.036.
[15] Vassileva I, Odlare M, Wallin F, Dahlquist E. The impact of consumers' feedback preferences on domestic electricity consumption. Appl Energy 2012;93:575–82.
[16] Ek K, Söderholm P. The devil is in the details: household electricity saving behavior and the role of information. Energy Policy 2010;38:1578–87.
[17] Sardianou E. Estimating energy conservation patterns of Greek households. Energy Policy 2007;35:3778–91.
[18] Palm J. Energy efficiency in households. Policy, implementation and everyday activities. 1st ed. New York: Nova Science Publishers, Inc; 2011.
[19] Ndiaye D, Gabriel K. Principal component analysis of the electricity consumption in residential dwellings. Energy Build 2011;43:446–53.
[20] Owens J, Wilhite H. Household energy behavior in Nordic countries – an unrealized energy saving potential. Energy 1988;12:853–9.
[21] Abrahamse W, Steg L, Vlek C, Rothengatter T. A review of intervention studies aimed at household energy conservation. J Environ Psychol 2005;25:273–91.
[22] Poortinga W, Steg L, Vlek C, Wiersma G. Household preferences for energy-saving measures: a conjoint analysis. J Econ Psychol 2003;24:49–64.
[23] Yohanis YG. Domestic energy use and households' energy behavior. Energy Policy 2012;41:654–65.
[24] Vassileva I, Wallin F, Dahlquist E. Understanding energy consumption behavior for future demand response strategy development. Energy 2012. http://dx.doi.org/10.1016/j.energy.2012.02.069.
[25] http://www.manodo.se, 2012-11-30.
[26] Vassileva I, Wallin F, Ding Y, Beigl M, Dahlquist E. Household indicators for developing innovative feedback technologies. In: Proceedings of the innovative smart grid technologies (ISGT Europe). 2011 2nd IEEE PES international conference and exhibition on innovative smart grid technologies – Europe"; 2011. p. 1–7, 5–7 December. doi: http://dx.doi.org/10.1109/ISGTEurope.2011.6162715.