Cultivating Energy Literacy—Results from a Longitudinal Living Lab Study of a Home Energy Management System

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ABSTRACT

This paper presents results of a three-year research project focused on the emplacement of Home Energy Management Systems (HEMS) in a living lab setting with seven households. The HEMS used in this study allowed householders to monitor energy consumption both in real-time and in retrospective on the TV and on mobile devices. Contrasting with existing research focused on how technology persuades people to consume less energy, our study uses a grounded approach to analyze HEMS emplacement. As an important result, we present here the issue of 'energy literacy'. Our study reveals that, by using HEMS, participants became increasingly literate in understanding domestic electricity consumption. We discuss the role HEMS played in that process and how the acquired literacy changed energy consumption patterns. We conclude that literacy in energy consumption has value on its own and explain how eco feedback system designs can benefit from this understanding.

Author Keywords

Energy Monitoring; HEMS; Energy Literacy

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

General Terms

Human Factors; Design

INTRODUCTION

In recent years, we have witnessed growing research efforts to design and understand the role of interactive eco feedback systems [6, 8, 12, 19] and support the larger goal of enhancing modern society's energy efficiency. For the field of sustainable HCI, a central problem to address is the immateriality of energy [32] and how to make it a visible entity [8]. Electricity is an invisible and abstract force, entering the household via hidden wires. It has been described as being 'doubly invisible' [5]. On the one hand, electricity is conceptualized as a commodity, a social necessity or a strategic material [36]. On the other hand, energy consumption is part of inconspicuous daily routines and habits [37] that makes difficult for people to connect concrete behavior or actions to the energy consumption patterns.

Against this background, interactive feedback systems are ascribed a high value, given their potential to motivate behavioral change and support learning processes [8, 12, 15, 35]. Darby, for instance, shows that feedback causes energy savings between 5%-15% [8, 9].

In sustainable HCI, to this day, most research is framed by persuasion theory [4, 12, 19]. Even though they acknowledge the achievements of this approach, Brynjarsdóttir et al. [4, 40], have also shown that this perspective alone limits our understanding and our visions for eco-feedback systems. Studying only 'what systems do to people', i.e. how eco-feedback systems reduce energy consumption, cannot account for 'what people do with systems', i.e. how people in daily life appropriate eco feedback systems and the practices that emerge from this appropriation process. In our research, we therefore want to explore and apply a grounded approach [20] to the appropriation of eco feedback systems.

As one of the very early attempts to qualitatively study the usage of HEMS in the long term, this research builds on a 6 months pre-study and the development of a custom Home Energy Management System (HEMS), which we rolled out in a living lab setting to seven households over a period of 13 months. Through TVs, PCs, smart phones and tablets based interfaces, the system provided feedback on real-time and past electricity consumption, both on a household and an appliances level. We captured users' experiences with the system through on-site interviews and workshops, and we analyzed the data using an open-coding process, as suggested by grounded theory [20].

In this paper we focus on a theme that emerged from our analysis, which we phrase *energy literacy*. We explain here what is meant by this term, how the introduction of HEMS

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creates energy literacy and how the construction of energy literacy is a personal endeavor that empowers people to reflect and act on their energy consumption. We conclude that energy literacy has value in its own and make suggestions on how HCI designs could take into account and benefit from this perspective on eco-feedback systems.

RELATED WORK

Over the past 20 years, feedback mechanisms have been widely studied in environmental psychology, where the positive effect of feedback has already been demonstrated since the time of paper-based electricity bills [13, 43]. The explanation of the positive effects has been typically based on rational choice models or norm-activation models [1, 38].

In relation to the long history of environmental research, the history of Sustainable Interaction Design (SID) is comparatively short, but extremely active [3]. In recent years, several studies investigated home energy consumption [7, 33, 34, 40] and effects of interactive eco feedback [19, 28, 31]. The spectrum of eco feedback approaches and systems promoting a sustainable life style became very wide, reaching from artistic solutions like the PowerAware Cord [21], over pragmatic ones like the Kill-A-Watt and Watt-Lite [29] to HEMS that integrate multiple features in a home-oriented system of appliances.

Conceptually, most SID approaches adopt the dominating stance of environmental psychology, explaining energy consumption by means of the individual, rational behavior [12, 19, 38]. Translating from the theoretical models into design, these approaches usually make use of Fogg's concept of persuasive technologies, concerned with 'how behavior modification can be induced by intervening in moments of local decision-making and by providing people with new rewards and new motivations for desirable behaviors' [17]. The merit of this research thread is that it outlines the challenge of behavioral change, which goes beyond the design of usable and easy-to-use systems. Initial design concepts of persuasive feedback systems had yet to recognize the diversity of individual motivations and the fact that behavior change takes place in a series of stages. Motivational feedback needs to appeal to the specific stage of behavioral change of people [25]. Authors like Wilhite et al. [43] even point out that energy consumption is not an objective reality. To deal with changes in consumption patterns, we need to understand the phenomenon of energy as it is constructed by the people themselves [30].

In terms of studying sustainable HCI in the field, an important shortcoming of current research is that most studies focus on short-term engagement in lab environments, but rarely studied real life deployments of high-fidelity prototypes in long-term studies [21]. A few studies coming from disciplines other than HCI have approached the emplacement and impact of HEMS, aiming to understand how reductions of energy consumption work in the wild [22, 23, 41]. Their findings show that there is no simple cause-effect relationship between feedback and behavioral change as persuasion models propose, and that the emplacement of such systems is a subtle and complex process, which is difficult to anticipate and simulate in lab settings.

These results clearly show an inmediate need for HCI research for contextual, longitudinal approaches to explore the emplacement and effects of HEMS on the knowledge, habits and routines of people [40]. There is a need for ethnographically oriented studies, to approach long-term appropriation processes that emerge in the wild through the deployment of eco feedback systems.

One major consequence we should draw in SID, is that we should ask not only *how feedback affects the people*, but also *what people do with the feedback in daily life*. In our research we addressed this need and apply for that a grounded theory approach [20] to the phenomenon of HEMS emplacement in the context of a living lab setting.

RESEARCH DESIGN

Setup and Methods

The work described in this paper was conducted as part of a 3-year project focusing on the research and development of concepts and strategies of in-house information systems, including the development of HEMS. Froehlich stated that for high fidelity prototypes in context of energy monitor systems, field deployments are more appropriate than laboratory settings, especially for testing and evaluating in the long run [19]. Motivated by this, and to address the complexity and situatedness of HEMS deployment in real-life environments, we applied a living lab approach [2, 18, 26].

Living labs involve users at an early stage in the design process for 'sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts' [2]. The long-term cooperation between researchers, users and other relevant stakeholders allow to bring users and technology into an open design process in real life environments [18], supporting long-term cooperation, co-creative research and a continuous, long-hauled study of user experiences.

Starting off from a pilot study we developed a HEMS, conducted user research and, in collaboration with the users, further explored the HEMS design and appropriation. As shown in figure 1, the entire process included a number of different activities:

The **pilot study** was conducted between November 2009 and May 2010 with an independent set of households with 46 participants in 16 homes. We provided an out-of-the box smart meter infrastructure that measured the energy consumption on an appliance level over a period from 10 to 15 days. Participation was voluntary and the selected households varied widely in demographics (age, gender), living arrangements (home owner, apartments) and in terms

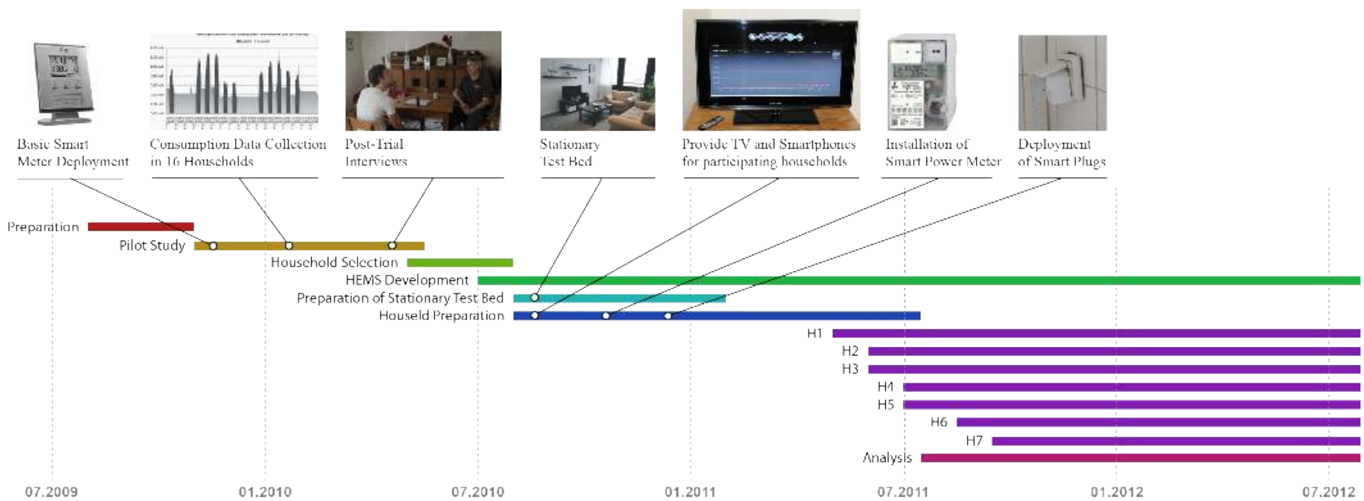


Figure 1: Study Design

of social groups and different professional backgrounds. Following the tests with the devices, we used the collected consumption information to run workshops at the households with the goal to uncover individual practices. The workshops were entirely audio- and partly videotaped. We analyzed the data using media annotation tools in an open coding fashion, to find common patterns and categories that bring about understanding how people make use of eco feedback and how they relate to and live with such system. We reconstructed existing energy practices and strategies of sense making and accounting for consumption based on the collected metering information.

For **household selection**, to prepare the next, longitudinal living lab study, we started a comprehensive selection process. Information about the study was spread in the local newspaper and via radio stations. Prospects were asked to submit an online questionnaire with basic information. Telephone and on-site interviews were conducted to gather additional information about the households. Also taking into account technical constraints and prerequisites, such as the availability of Wifi and the possibility to install both smart meters and device level meters, we finally selected 7 homes with 16 participants. All households were located near the city of Siegen, Germany, representing a typical sample for this region [14]. This sample size, while providing a range of different household settings, allowed us, within the project's resource limitations, to distribute entire HEMS systems including a set of interactive devices. With an overall planned period of 24 months, the sample also was expected to produce a large body of data that would allow for an in-depth analysis.

For our initial **HEMS development**, we based the design on the empirical analysis within the pilot. The technical setup for the HEMS comprised a number of different components:

First, capturing the households' overall power consumption required the replacement of the existing mechanical power meters by digital *SmartPowerMeters* that allow capturing overall energy consumption of the respective households. Once installed, we were able to receive measurements by an optical communication module of the *SmartPowerMeters*. We used Ethernet gateways as a coupling element and in-house *PowerLine* communication to make meter readings accessible throughout the home network. During operation, the meters continuously send out consumption data using *SmartMessageLanguage* (SML) protocol via message push.

Second, to capture power consumption on appliance level, *SmartPlug* sensors were used to provide finer grained measurements. The *SmartPlugs* can easily be installed by plugging them between the power socket and the appliance plug. Through an autonomous ZigBee network, the *SmartPlugs* provide information about current power consumption. They also store historical energy consumption of the connected appliances. Additionally, the hardware allows switching appliances on and off.

Third, HEMS comprises a Media Center PC, which we connected to the households' main TV. This PC acts as a *SmartEnergyServer* managing, storing and processing measured energy data. The server also runs the HEMS' *EnergyMonitor* software to provide a graphical user interface to visualize the collected information. The software was designed in a way that allowed straightforward interaction and required no prior knowledge or special training. It has been continuously developed throughout the project following participants' feedback and our observations. In its current version, the energy monitor includes seven screens that show readings from the *SmartPowerMeter*, real-time power consumption information, historical energy consumption and a comparative tag cloud. The latter allows users to freely assign tags to *SmartPlugs* and thus grouping them according to personal preferences. Selected views of the *EnergyMonitor* are shown in Figure 2.

Fourth, to interact with the *EnergyMonitor,* users were able to access the feedback on a common interface when calling the *EnergyMonitor* from their TV, PC, tablet devices or smartphones. TVs and smartphones were provided to the households if not already available.

Once selected, the **preparation of households**, was a major effort, too, as the technical conditions and premises varied considerably among the different households and we needed to standardize the infrastructure in order to create basic conditions for our HEMS throughout the entire project period and throughout the participating households. To install the *SmartPowerMeter*, the support of respective electricity providers was required. In advance, we analyzed several types of electricity meters and their technical details to ponder implementation costs of communication protocols and facilities for our HEMS. The deployment of the *SmartPlugs* was carried out during collaborative workshops with householders and our project team.

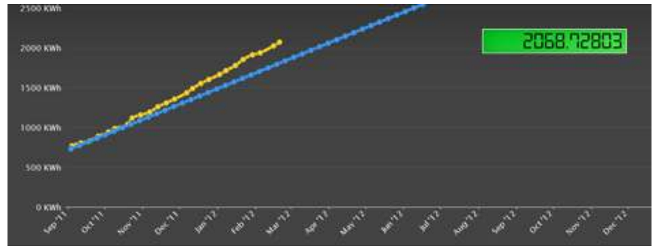
Additionally we implemented a second, **stationary control test bed** in our lab. This test bed was equipped similarly to the participants' households in terms of technology, so that we could run tests under similar technical conditions before rolling out a new HEMS version and thereby eliminate technical problems.

After the households were chosen and equipped with the required technology, we started the **continuous investigation** of HEMS appropriation. We began by conducting semi-structured interviews with all participating households, to uncover existing knowledge, attitudes and motivations affecting energy consumption. The questions of the initial interviews focused on how participants managed electricity consumption at home. To this day, numerous activities within the participating households were conducted. This includes in-depth interviews, prototype explorations, user workshops and participatory observations of the usage of the *EnergyMonitor*. We frequently visited the households, supported them with technical problems and provided new versions of the HEMS when available.

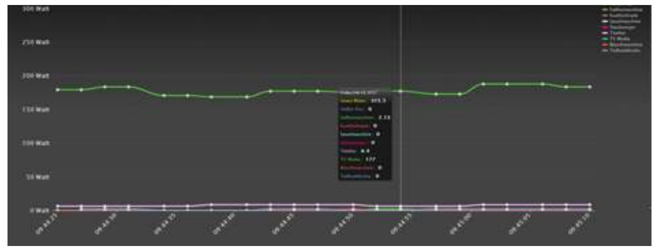
For **data collection**, our research followed a triangulation strategy looking at the phenomena from different angles [16] to understand the subtleties of HEMS emplacement.

First, to unobtrusively collect data in real-life settings, we studied the integration of HEMS into the local context and the usage over time by evaluating usage statistics. For this, we used the log files of the *SmartEnergyServer*.

Second, to study the overall user acceptance, we conducted an AttrakDiff survey to learn about the perceived usefulness and easy of use as well as hedonic qualities of our HEMS [10, 24]. The results of this survey will be described in another publication but generally show the high level of acceptance of the system.

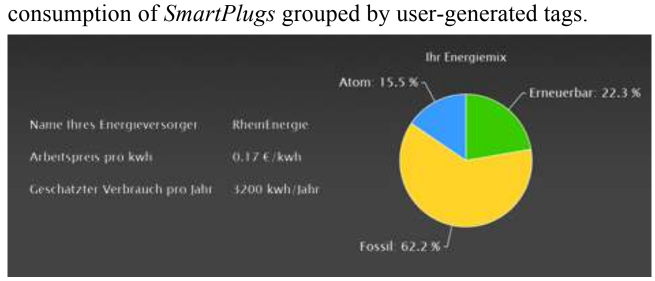


Meter information: The landing page of the feedback tool shows a graph comparing the factual energy consumption of the household with an anticipated prognosis on basis of consumption of the last years. Additionally, it shows the meter counter.

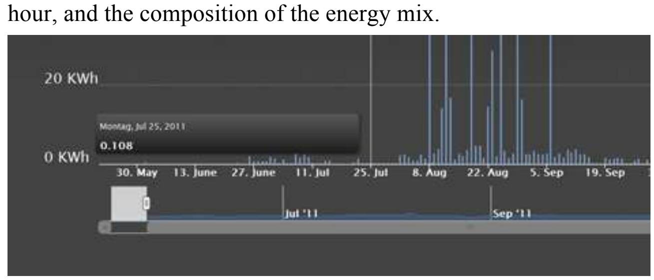


Real-Time Power Information: This screen provides real-time visualization of the current power usage, measured by the *SmartPlugs* and the *SmartPowerMeter*. The visualization can be filtered according to tag groups.

Comparative Tag Cloud: The tag cloud shows sums of consumption of *SmartPlugs* grouped by user-generated tags.



Contract Information: This screen shows the estimated consumption for the current year, based on last years' consumption, the utility providers' name, the price per kilowatt hour, and the composition of the energy mix.



Historical Energy Consumption: This screen shows the historical energy consumption data of chosen tag groups or data from the *SmartPowerMeter*.

Figure 2: Interaction Concept of HEMS

Third, to understand households' dynamics [22, 23, 42], we studied emerging practices and critical incidents [39]. Here we relied on qualitative data captured during interviews, informal talks and observations from on-site visits. Overall, we audiotaped 63 interviews and 32 workshops with a total length of over 200 hours. Several million datasets on energy consumption of households and appliances were gathered over a time span of 13 months. Furthermore, households increasingly accepted remote access to the *SmartEnergyServer* even in absence, which was helpful to install new releases or prepare follow-up visits and to observe the usage of new features.

For **analysis** of the collected data we followed an open coding process and the constant comparative method as suggested by grounded theory [20]. With our project team we conducted coding workshops and used the results as input for theoretical sampling in further investigations. While this analysis is an ongoing process and we plan to present additional aspects from this research in forthcoming articles we present in the following a first theme that evolved early in this work.

RESULTS: ENERGY LITERACY

The analysis of the corpus of data collected in our work revealed several aspects of the appropriation process around HEMS. An important element that was particularly visible was a continuous process of learning as the natural result of the problem solving activities, a process which led to a growth of knowledge and competence. We framed this observed issue with the concept of 'energy literacy'. In the following we describe, illustrating with extracts from transcripts, the different categories related to this new form of literacy promoted by the use of HEMS. We detail what is it that our participants learned, how they acquired this knowledge and what the impact is of this new competence in existing practices.

What People Learned

Appliance Level Consumption

As became apparent by the stark contrast in the interviews before HEMS installation and after, HEMS allowed people to learn about electricity consumption for their home appliances and ascribe meaning to information presented by HEMS. They became literate and thereby much more specific and expressive in talking about their home energy use.

We use the following two parts, taken from interviews with the same person of household 2, as an example for the growth of knowledge and capabilities of householders regarding their individual energy literacy. The first excerpt is taken from the initial visit of the project, where we wanted to learn more about their individual housing context as well as their understanding of their energy consumption. Here, the person explains his energy consumption.

I don't really know how much the receiver consumes. The TV, because it's a plasma TV, consumes quite a lot. Other than that ... the refrigerator, I don't know how much that consumes, I don't think it's that much. […] I'd also say the stove, I've never really paid attention to its consumption. I would also guess, the TV consumes the most and in the kitchen, the stove. But I'm not that sure about that.

The second excerpt is taken from an interview with the same participant after a HEMS deployment of 94 days during which the system was accessed on 41 days (Figure 2).

[it was beneficial] seeing how much each device consumes and then to think about it […] Alarming how much we use in the evening. […] The TV consumes quite a lot, I have to say, almost 600 Watt [...] and when the oven rockets up to 3000 Watt […] And the dryer, I would have said it needs quite a bit, but the consumption actually was not that high. I thought it goes up to 2000 Watt or so […] if it does full heat. But then it was only 400 Watt.

Here, the participant is able to de-aggregate his individual consumption on appliances level. He uses 'Watt' as a unit to explain and compare electricity consumption and to make value statements. His explanations are from memory, showing that the knowledge about electricity consumption has been deeply internalized and his competences to assess his own 'energy system' grew by using HEMS.

For individual appliances, participants were also able to identify stand-by consumption, as described in the following example.

We also recognized that the water kettle […] yes, that it even consumes electricity if it is at zero. That means, if it is only plugged-in, not being used. Then it already has 40 Watt or so, or I think even 60 Watt. That is unbelievable.

	Days of exploration	HEMS access total	Ø access per day	Ø HEMS access every X days
H1	321	124	0.39	2.59
H2	155	98	0.63	1.58
H3	311	25	0.08	12.44
H4	244	21	0.09	11.62
H5	314	68	0.22	4.62
H6	400	181	0.45	2.21
H7	408	107	0.26	3.81
	∑ 2153	**∑ 624**	**Ø 0.30**	**Ø 5.55**

Figure 3: HEMS usage for all households

These examples are typical for all participating households. Throughout the study, householders were growingly able to draw a detailed picture of their local energy system after using HEMS. Participants were able to specifically name consumption data of their appliances by using units of consumption and comparatively relate consumption information of different appliances.

Idle Current Consumption

Beyond consumption on an appliance level, we observed that participants over time developed an understanding of their entire household power consumption. HEMS provided overall consumption information on the screen 'real time power in formation' that became most popular (Figure 4). Participants commonly used the information as a reference value by comparing the current consumption with previous values they knew about and considered legitimate.

Interviewer: Does the displayed information mean anything to you? What kind of relevance does it have?

P1: […] 300 Watt, currently, for mid-day is not so much. Usually we have 500 Watt … I memorized this.

When speaking about idle current, five of seven households differentiated between day and nighttime. Here, nighttime referred to the time when everybody was in bed and only always-on appliances were switched on, as the following extract shows:

I am interested, of course, to know in the evening, now everybody is in bed, now I quickly spy [using HEMS' live monitor] […] I was eager to do this. We usually then had about 300 Watt.

Basic Knowledge

In addition, beyond consumption information on appliance and household levels, we observed that through HEMS people gained basic knowledge of issued related to domestic electricity consumption. This includes the price of one Kilowatt hour (KWh), costs on past electricity bills, consumption on past accounting periods, name and contract duration of the current energy provider and the share of renewable energies in the electricity mix. Householders could easily access this information on the screen 'contract information'. This screen was least frequently accessed, but nevertheless gained the users' attention. For some years, German law regulations require this information on the energy paper bills, yet only availability through HEMS supported a sustained and aware knowledge in our households.

How People Learned

Learning in Retrospective

In our study we observed that participants reflected their energy consumption in retrospective, by data displayed by HEMS. Participants' contextual knowledge of routines and habits helped them to ascribe meaning to visualized data. Thereby, they could establish relations between energy consumption and specific activities in the past, as the following example shows in which the participant analyses his historical energy consumption:

What date was this? That is October 9th. There the curve goes up. I guess that I made the apple juice then. […] You can read this off the graph. And also now with the recording [off individual appliances] even more […]. And I am of course shocked that I, by boiling down the apple juice, [caught up] with the anticipated consumption. [laughs] First you have all the work. Starting with the picking [of the apples] and the process and we use all this time. And if you go to the shop instead, you buy a liter of apple juice for 99 cents.

As shown in the excerpt with HEMS' support, using electricity can be reflected in retrospective and suddenly become a value laden activity.

Learning in Situ

Besides the retrospective interpretation of electricity consumption, as described in the previous section, participants also used real-time feedback to analyze their energy consumption, as in the following example.

Yes, I mean, now things are switched on. Let's turn off the light then we'll be able to see a reaction [turns off the light, the display of the energy monitor goes down by 100 Watt]. There, it's at 600 Watt. But that does surprise me […] we'll see [Turns the light back on. The curve goes up again]. It really does. Yes, that's 100 Watt. That's a lot. So let's turn it off!

In consequence of HEMS introduction, people developed abilities to make more informed decisions on their energy consumption.

Learning by Comparison

Once participants learned about electricity consumption of one appliance, they started comparing the appliance with other appliances. Also, they tried to understand the share in consumption that one appliance has within the group of devices in the same category. One participant, for example, wanted to know how much electricity all lightning consumes after he measured the ceiling light in the living room.

Learning by Service

Aiming for understanding their electricity consumption, participants additionally grouped a number of appliances to understand consumption as a service that enables activities. The service, 'watching TV', for instance, can comprise the appliances TV, stereo amplifier, receiver and DVD player. 'Being in the living room' is another service that participants wanted to understand. In the following, such services became a reference to further analyze and estimate the household's consumption.

Learning from the Expert

In the households with multiple people, the person who was our first contact person and the main user of the system became the energy expert, whom other householders talked to about electricity consumption. Here the usage of HEMS triggered communication among family members about energy consumption. We learned, for instance, that in some cases not all family members used HEMS independently, but instead asked their 'energy expert' questions concerning consumption. The expert then either gave advice or supported the use of HEMS.

She asks me and then I said: Here you see how much the laundry machine consumes or how much the dryer consumes, or so.

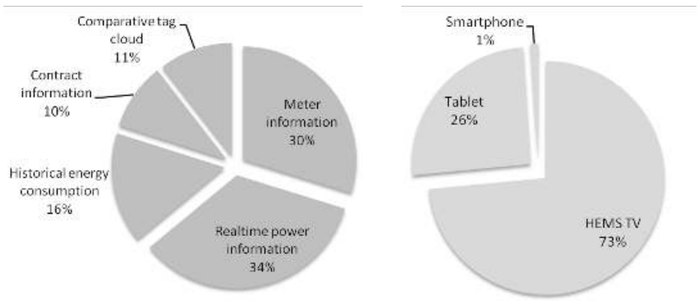


Figure 4: HEMS page impressions (left); HEMS usage by devices (right).

Also, in some cases, the 'energy expert' became the controller, or teacher who enforces rules for domestic energy consumption.

Yes, now that I know that my daughter used the PC and listened to music at the same time and then she also was on the phone and went outside to the balcony for the call. And then I just say: Hey, there are already 100 Watt from your room alone. Either you switch off the devices or you stop the phone call. That's a thing: Phone calls with the teenagers these days go on for half an hour or an hour and the devices run anyways.

Learning in Collaboration

As we witnessed during our on-site studies and as we learned from interviews, householders developed mutual practices to understand their energy use. Householders discussed energy consumption and mutually developed strategies for optimization. Here, for instance, one person would monitor HEMS on the TV, while the other person would walk around the house to turn appliances on and off.

When I had the TV on, or, I also looked at it in between, and then I also checked with my wife when we for instance turned on the coffee machine, how that shows up on the curve. Or when she intentionally went downstairs and then turned on the laundry machine, we could track the impact.

Sustained Learning

In the households, learning about energy consumption became part of daily routines and was a sustained activity throughout the year. The TV became the main device to access HEMS as it allowed for a seamless integration with existing practice.

Householders used HEMS when watching TV. They, for instance, checked their current energy consumption before or after watching TV or during commercial breaks (Figure 4).

Interviewer: And did you have special occasions to check [HEMS]?

P2: No, just spontaneously when I watched TV. If the TV was on anyways, then I turned on the system [switched to EnergyMonitor] in the background. So, not always, but especially then.

Impact from Learning

Change of Routines

The newly acquired skills impacted householders' energy consumption behavior. They changed practices and routines, which are part of habitual domestic life. They would, for instance, explain:

Yes, well, we did consciously leave the light switched off here in the hallway. Usually we fully let the light burn in the evenings here in the hallway; and we were upstairs and our son wasn't here yet. Yes, why should we have the light turned on?

This indicates that HEMS impacted the way people use electricity and, as in the case above, identify and change wasteful practice. Also, as in the following example, they considered alternative practice that does not require electricity:

My wife is very conscientious. We already talked about drying as much as possible in the basement [by hanging clothes]. We just checked again what impact that [the dryer] has.

Rearrangement of Existing Devices

Another common observation was that once householders had established an understanding of their local energy system through HEMS they conducted energy conservation activities that optimized the rearrangement of appliances. The following case taken from an evaluation workshop illustrates this effect:

P1: Especially upstairs in the area, as I said before, I don't let the TV in standby [...] but that I really switch it off. For this I put the remote control where I switch it off completely.

We also observed that participants used power strips to merge devices and to be able to switch them off together. Participants also changed their configuration to achieve previously identified saving potentials. Here, not only appliances, which are immediately accessible for domestic use, came in focus. We observed that people also took into account constituent elements of the household, like heating:

I've separated the heater downstairs, because the circulation pump is always working and it consumes about 70 watt, so I installed a timer. Only if the timer is on, then the pump will also turn itself on.

Choice of Appliances

Beyond the change of routines or the changes in using existing devices, HEMS also increased the awareness and the knowledge about how much energy could be saved by replacing an appliance with a more energy efficient one. As the following example about a vacuum cleaner illustrates, the new skills influence future buying decisions.

It's not like we're going to vacuum less now [laughing], but I would say that the next choice of vacuum cleaner will be influenced by its [electricity] consumption. And not necessarily, like, it runs at 1200 watt, [means that] it must be good, but instead that you might say, this vacuum cleaner running at 700 or 800 watt might actually be more effective, because technology also evolves.

DISCUSSION

Our study confirmed previous statements about the knowledge deficit concerning energy usage within the home [8, 38]. As we described in the related work, sustainable interaction design has mostly applied persuasion theory [4, 12, 19] as a theoretical lens. Our results further provided empirical confirmation for the relevance of learning in eco feedback [19] and hence, for the importance of applying learning theories to frame the problem of sustainable interaction design. Learning and feedback closely relate [27]. Feedback can provide new information for the learning process [19], and it allows people to learn about the connection between invested resources and consumption and is therefore essential [8]. This connection represents an important precondition for an informed reflection about the actions that may lead to significant reductions in energy consumption.

Compared to the previous feedback through paper based energy bills, the HEMS was steadily used and played a major role in cultivating what we termed energy literacy, understood as the development of a competence to deal with and make sense of energy in relation to a local, personal frame of reference. As we have shown above, the usage of HEMS enabled householders to develop a better understanding of their electricity consumption. This covers both improving general and theoretical knowledge about energy as well as promoting the accurate understanding skills concerning the own energy consumption. In our study, participants developed an increased competence to trace back energy flows and use it for overall energy management.

The growth of energy literacy could be described as a co-evolving process of mutual influences between accurate and trustworthy information about the own energy system provided by HEMS and the reflection and contextualization of this information. In that sense, we can frame our studies as an instance of case-based learning. As outlined by Dewey [11], case-based learning has the structure of an inquiry where the starting point for learning is a personal problem, a puzzle, or a doubtful situation that to one wishes to solve. The progress of inquiry is twofold: On the one hand, one acquires better understanding of the context and, on the other hand, one acquires better understanding of the general and theoretical knowledge by living an experience. In our case, participants progressively made a connection between general energy consumption information and the context of their daily life. Dewey explains that learning, to be meaningful, requires a fulfilling experience where action and perception are connected and not fragmented. In acting around energy consumption, this fragmentation can easily take place, for instance, if one becomes aware of wasteful consumption, but could not act upon it or if one is forced to make a decision, yet does not have the right tools to inquiry the situation and connect it with previous experiences.

Beyond personal consumption, energy literacy can potentially play an important role in empowering people, making them informed citizens that have the knowledge to participate in the societal dialogue on managing energy resources. Here, the idea of encouraging energy literacy responds to the repeated calls by the sustainable research HCI community to allow users to take part and understand the values that are hidden in energy saving technologies.

The living lab approach created several challenges for the project, due to the high expenses for technical supervision and support of participants. Fostering social contact with households to maintain engagement over study period required significant efforts from both sides. Additional resources were needed to ensure ongoing system stability. In spite of these challenges, the use of a living lab approach proved to be extremely useful to explore the complex interplay of HEMS with practices of daily life as well as to uncover aesthetics and feelings towards the system.

Implication for Design

In our study, HEMS played an important role in providing measured data as a resource for people to develop energy literacy. For systems, to be able to play this role, HEMS needs to be weaved into daily life and consider the particularities of competence development. Based on our experience, we propose six principles to inform the design of future HEMS:

1. **Allow for Horizontal Comparison:** HEMS should provide views that show appliances of the same type of category. Thereby, the user could, for instance, compare the lighting in the living room with that in the sleeping room.
2. **Allow for Vertical Comparison:** HEMS should provide functionality to connect a specific device belonging to one or more specific activities to other devices that also belong to these activities. Thereby, users could track energy consumption related to activities that include multiple appliances.
3. **Provide Real-Time Feedback:** HEMS should link immediate feedback about current energy consumption with energy management actions so that users can learn in-situ and take immediate response. Learning would occur instantly and action and perception would not be fragmented.
4. **Provide Retrospective Feedback:** HEMS should provide users information about past consumption. In this way, HEMS increases the awareness and the knowledge of energy consumption in relation to

routines, habits or special events. Such feedback supports making future informed energy-related decisions.

5. **Support the Construction of Personal Consumption Language:** HEMS should provide personal reference values in order to create a connection between general knowledge and the people's contexts. The system, for example, could include individually defined metrics or allow redefining comparable groups and classes. This would allow people to analyze energy consumption in their personal language.
6. **Take the Energy Literacy Levels into Account:** HEMS should take into account that the people's energy literacy might vary. HEMS could provide different entry points ranging from novice to expert users or, following the idea that literacy develops from the use of the system, change over time. Additionally, the system could support different modes of interaction depending on the literacy level.

CONCLUSION & FUTURE WORK

In this paper, we have presented results from a longitudinal qualitative study of the emplacement of a home energy management system that has been rolled out for 13 months in a living lab setting in 7 households.

In HCI, a central research focus was to explore, how technology could persuade people to consume less energy. Our focus, 'what people do with technology', allowed us to uncover appropriation of HEMS from a different angle. We followed a grounded approach and empirically identified the issue of energy literacy as an important issue for eco feedback systems. This aspect, while mentioned in previous research, had before not been empirically studied in a long-term field inquiry. Based on our findings, we have proposed implications for the design of future HEMS.

Our own future work will include further analysis and development of our HEMS installation and also describe other aspects of HEMS appropriation beyond the theme of energy literacy. In general, we strongly believe that a closer look into existing learning theories might beneficially support the design of HEMS and other eco feedback systems. Recent work by He et. al [25], for example, argued that motivational feedback needs to appeal to the specific stage of behavioral change. An interesting extension to this view, following our study, would be to study stages of energy literacy and specifically investigate how energy literacy develops. Thereby, we would be able to address the specific needs and current energy literacy level of people. In the longer term, along with the increasing prevalence of HEMS, it is an open question how and if society's average level of energy literacy might change and what this evolution means for the design of eco feedback systems.

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