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What People Do with Consumption Feedback: A Long-Term Living Lab Study of a Home Energy Management System

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One of the great societal challenges that we face today concerns the move to more sustainable patterns of energy consumption, reflecting the need to balance both individual consumer choice and societal demands. In order for this 'energy turnaround' to take place, however, reducing residential energy consumption must go beyond using energy-efficient devices: More sustainable behaviour and lifestyles are essential parts of future 'energy aware' living. Addressing this issue from an HCI perspective, this paper presents the results of a 3-year research project dealing with the co-design and appropriation of a Home Energy Management System (HEMS) that has been rolled out in a living lab setting with seven households for a period of 18 months. Our HEMS is inspired by feedback systems in Sustainable Interaction Design and allows the monitoring of energy consumption in real-time. In contrast to existing research mainly focusing on how technology can persuade people to consume less energy ('what technology does *to* people'), our study focuses on the appropriation of energy feedback systems ('what people *do* with technology') and how newly developed practices can become a resource for future technology design. Therefore, we deliberately followed an open research design. In keeping with this approach, our study uncovers various responses, practices and obstacles of HEMS use. We show that HEMS use is characterized by a number of different features. Recognizing the distinctive patterns of technology use in the different households and the evolutionary character of that use within the households, we conclude with a discussion of these patterns in relation to existing research and their meaning for the design of future HEMSs.

RESEARCH HIGHLIGHTS

- We developed an own Home Energy Management System (HEMS).
- We rolled out our HEMS system in a living lab setting to seven households over a period of 18 months.
- Our System provides feedback through TV, PC, smartphone and tablet-based interfaces.
- This allowed us to explore 'what people *do* with HEMS in daily life'.
- We identify and discuss nine meaningful categories of appropriating HEMS.
- Based on our results, we discuss potentials for the design of future HEMSs.

Keywords: user studies; empirical studies in interaction design; sustainability

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1. INTRODUCTION

In March 2011 the European Commission (EC) adopted a new edition of the *Energy Efficiency Action Plan* with the global objective of counteracting climate change by improving energy end-use efficiency as a means to reduce primary energy consumption and, consequently, the mitigation of CO_2 and other greenhouse gas emissions (European Commission, 2011). In this plan, special emphasis is put on residential energy consumption which accounts for >20% of overall energy usage in the EU (according to Erickson *et al.* (2013), it is 37% in the USA), and in terms of absolute consumption continues to grow. One measure chosen by the EC to promote energy savings is the enforcement of 'smart metering', the electronic measuring of electricity consumption. The aim here is to provide end-users with individual meters that accurately reflect real-time energy consumption.

In making energy consumption visible to the consumer, smart metering addresses a central problem of modern energy use (Darby, 2001). Indeed, energy is considered 'doubly invisible' to householders (Burgess and Nye, 2008): First, energy is conceptualized as a commodity, a social necessity or a strategic material (Sheldrick and Macgill, 1988), and hence is construed as an abstract entity. Secondly, rather than being an outcome itself, energy consumption is a by-product of inconspicuous daily routines and habits (Shove, 2004), making it difficult for people to connect specific behaviours to the energy they consume.

To make consumption visible, interactive feedback systems are considered crucial, as they increase energy awareness, motivate behavioural change and support learning processes (Darby, 2001; DiSalvo *et al.*, 2010; Fitzpatrick and Smith, 2009; Mankoff *et al.*, 2007). Feedback provision, it is argued, can raise awareness and create knowledge that may bring about change in energy-relevant behaviour, resulting in a decrease of consumption (Wilhite and Ling, 1995). Studies report the potential of energy savings ranging 5–15% (Darby, 2001, 2006). Following several simple feedback solutions such as 'Kill-A-Watt' (Jönsson *et al.*, 2010), a variety of Home Energy Management Systems (HEMSs) have emerged, which provide users several options on how to present the feedback information (Rossello-Busquet and Soler, 2012).

Despite largely positive results from feedback systems in academic studies, the widespread deployment of smart meters capable of providing such feedback remains an open challenge for the domestic market. Publicly funded pilot studies, as well as those conducted by large energy suppliers, show that smart meters lack market acceptance (Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE, 2010). One of the reasons identified is that existing initiatives governing smart meters, smart grids and similar technologies pay too little attention to the desires, needs and practical purposes of users (Bundesverband Verbraucherzentrale, 2010; Franz *et al.*, 2006). Indeed, a scan of publications on smart grid and HEMS technologies (Massoud Amin and Wollenberg, 2005; Rossello-Busquet and Soler, 2012) shows that user issues tend to be marginal to the discussion on design decisions. The German Association for Electrical, Electronic & Information Technologies or VDE summarizes the problem (in relation to smart grids) as follows:

> *So far, the discussion about the use of smart grids in private households gives priority to privacy issues. Ergonomic aspects, however, have to be considered with an equally high priority, since usability and the market acceptance depends on it. Only a few consumers have experience with smart grids. Accordingly, there is currently almost no knowledge available about ergonomics and accessibility.* (Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE, 2010. *Translated by the authors*)

The reasons for this blind spot have to do with assumptions about the user. As Erickson *et al.* (2013) point out, the user often is presumed to be a rational actor. Brynjarsdóttir *et al.* (2012) argue similarly that existing research on energy feedback is primarily concerned with persuading people to consume less energy. Conceptually, this focus on persuasion creates a direct link between technological intervention and behavioural change, and hence is predicated on a form of technology determinism that fails to recognize the situatedness of practice and the agency of people (Dourish, 2004; Suchman, 2007). This determinism tends to isolate issues in order to operationalize the 'persuasion effect' and thus separates the phenomenon of energy consumption from its context in everyday life. To avoid the resulting narrowing of focus, it is important to ask 'what people do with consumption feedback systems', and in particular, how people appropriate such systems into their daily lives and how such systems shape patterns of consumption and the social practices of consumers.

Addressing these concerns, in this paper we present the results of a qualitative research approach (Strauss and Corbin, 1990), aiming explicitly to investigate the question of how consumption feedback is appropriated and woven into the complexity of people's daily life. Our research is based on a 6-month pre-study, (Schwartz *et al.*, 2013b) followed by the development of a custom HEMS, which we rolled out in a living lab setting to seven households over a period of 18 months. Through TV, PC, smartphone and tablet-based interfaces, our system provides feedback on real-time and past electricity consumption, both on a household and an appliance level. To explore the impact of our HEMS on domestic life, we analysed the data from on-site interviews and workshops using an open-coding process, as suggested by grounded theory (Strauss and Corbin, 1990). To obtain additional insights, we conducted a qualitative analysis of hardware and software adaptation by the users of the systems and we reviewed system usage based on log file analysis.

The rest of this paper is structured as follows: in Section 2, we present previous work that helped the framing of our study. Subsequently, we delineate our approach and methods. Section 4 presents the main results of our study, followed by a discussion of results and their implications for the design of interactive consumption feedback systems.

2. RELATED WORK

In recent years several related concepts have emerged in the literature to describe a new family of IT systems, which involve digitally measuring domestic resource consumption and making this information accessible to the user. The terms most used in the literature are smart metering technologies (Darby, 2010), in-home displays (Chiang *et al.*, 2012), energy monitors (Van Dam *et al.*, 2010), energy management systems (LaMarche *et al.*, 2011), electricity consumption feedback (Erickson *et al.*, 2013) or eco-feedback technologies (Froehlich *et al.*, 2010). These technologies are closely related to each other in terms of key design issues, historical development of practical implementation, theoretical underpinnings and their role in HCI research, as we will lay out in the following on an empirical as well as theoretical level.

Despite the absence of a naming convention, aforementioned systems share key design issues, which relate to the representation of data, the spatial and temporal aggregation/disaggregation, the historical and normative comparison, the topic of motivation support and the output medium and use context (Froehlich *et al.*, 2010; Jacucci *et al.*, 2009; Karjalainen, 2011).

- (i) Concerning *data representation*, for instance, pragmatic displays focus on highly accurate and informative feedback. They commonly use physical (e.g. kWh), economic (e.g. USD) or environmental (e.g. CO_2) units and also use graphs to make the feedback more informative. On the contrary, the primary aim of artistic visualizations like the 'PowerAware Cord' (Gustafsson and Gyllenswärd, 2005) relates to 'communicating a concern, rather than to showing data' (Kosara, 2007).
- (ii) The *spatial aggregation/disaggregation* allows one to break down the consumption to a room or appliances level. This e.g. makes it easier to detect energy gluttons like old freezers that produce large amounts of wasted energy (Froehlich, 2009).
- (iii) The *temporal aggregation/disaggregation* covers decisions such as the update frequency and temporal grouping (e.g. real-time, by day, week or month) of consumption data. Real-time information, e.g. helps to get direct feedback of actions. Other temporal aggregation fosters the detection of specific temporal patterns in energy consumption (e.g. day/night, workday/weekend, holidays, etc.; Froehlich, 2009).
- (iv) The design of normative comparison is closely related with the *motivation support and incentive design*. A lot of the design solutions became inspired and informed by environmental psychology and their findings to promote pro-environmental behaviour. In general, normative comparison refers to the feature of visualizing consumption in relation to someone else. e.g. the users' Facebook friends (Foster *et al.*, 2010) or others households in the neighbourhood (Egan *et al.*, 1996). This feature helps users to understand their consumption in the light of what is considered to be normal and persuade them to modify their behaviour to conform to social norms.

From a historical perspective, the predominant technological design strategies of smart metering technologies started with rudimentary displays and evolved quickly over time, nowadays covering a wide range in terms of their comprehensiveness. First-generation devices were rather simple energy monitors like 'Kill-A-Watt' and 'Watt-Lite' (Jönsson *et al.*, 2010), which presented the raw energy consumption of the total household consumption (smart meter solutions) or isolated appliances (smart plug solutions) on an LCD display. Typically, users only had the opportunity to switch between different units. By installing these displays in highly visible locations of households, they were supposed to raise awareness of energy consumption. More sophisticated feedback systems often are realized as web-portals (Erickson *et al.*, 2013) or smartphone apps (Weiss *et al.*, 2012), combining multiple features and data representations. While providing detailed information on household consumption, these systems typically do not include metering on an appliance level. In this regard, HEMSs (Van Dam *et al.*, 2010) go a step further by integrating various sensors and meters to provide feedback on different aggregation levels (Rossello-Busquet and Soler, 2012). In future, by combining concepts from consumption feedback, home automation and demand response research (LaMarche *et al.*, 2011), HEMSs are expected to become two-way solutions allowing for both: monitoring and controlling devices in the home.

In the HCI community, the new feedback systems are mainly discussed from a perspective of their capability to provoke energy savings. Moreover, some authors view this as their defining characteristic. For instance, Froehlich *et al.* define eco-feedback technology as a system that 'provides feedback on individual or group behaviours *with a goal of reducing environmental impact*' (Froehlich *et al.*, 2010 our italics). In this line of work, an important part of the approaches in HCI adopts the dominating stance in environmental psychology, explaining energy consumption by means of the individual, rational behaviour (DiSalvo *et al.*, 2010; Froehlich *et al.*, 2010; He *et al.*, 2010; Stern, 1992). In the field of environmental psychology, research on pro-environmental behaviour change has a long tradition. In particular, feedback mechanisms have been studied over the past 20 years, demonstrating the positive effects on energy savings since the time of paper-based electricity bills (Egan *et al.*, 1996; Wilhite and Shove, 2000).

Translating the theoretical models into design, some approaches in HCI make use of Fogg's concept of persuasive technologies, concerned with 'how behaviour modification can be induced by intervening in moments of local decision-making and by providing people with new rewards and new motivators for desirable behaviours' (Fogg, 2002). The merit of this research thread is that it outlines the challenge of behavioural change, which goes beyond the design of usable and easy-to-use systems.

Brynjarsdóttir *et al.* (2012), however, note that focussing on persuasion comes with a narrowing of vision that 'brings into sharp focus certain limited aspects of an otherwise far more complex and unwieldy reality'. This theoretical narrowing is accompanied by the danger of neglecting the plurality of theoretic stances in environmental research. Highlighting this plurality, notable work has been done by Jackson (2005), with a particular focus on consumer behaviour and behavioural change; Wilson and Dowlatabadi (2007), addressing consumption-related decision-making; Hinton (2010), with a special focus on comfort practices and their evolution, and Darby (2010) who put an emphasis on theories of feedback provision. Recently, in addition to individual-rationalistic explanations, it has been suggested that socio-technical and praxeological oriented approaches (Gram-Hanssen, 2010; Shove, 2004; Warde, 2005) are needed to get a complete picture of the complex topic of domestic energy consumption. In HCI, alternatively oriented lenses, for example, help to understand the phenomenon of energy as it is constructed by the people themselves (Kempton and Montgomery, 1982) and how feedback mechanisms can support making domestic energy consumption accountable (Schwartz *et al.*, 2013b). Further notable examples of the praxeological lens in sustainable HCI are, e.g., the work of Strengers (2011), Pierce *et al.* (2011) or Ganglbauer *et al.* (2013).

On the empirical level, a brief survey of the literature shows that empirical studies are commonly dominated by the persuasion stance. In environmental psychology especially that frame of reference is instantiated by the concept of pro-environmental behaviour change. Abrahamse *et al.* (2007), for instance, survey the literature to evaluate several intervention strategies like goal-setting, information or feedback concerning their effectiveness in terms of encouraging households to reduce energy consumption. In a similar vein, Darby (2006) surveys the literature to figure out what kind of feedback will be the most effective in terms of energy saving. Also meta-analyses like Fischer (2008) or Ehrhardt-Martinez *et al.* (2010) primarily aim to summarize existing feedback studies with regard to how much energy was saved.

While investigation into conservation effects represents the major focus in HCI, studies also tend to follow a more or less standard research design. First of all, they typically are short-term, small-scaled and lab-based (Froehlich *et al.*, 2010). In addition, they often have a strong design and usability focus, evaluating advanced and experimental technologies. Representatives of this kind of research include the Wattsup design study—an Facebook app providing social comparison that was evaluated by eight households over a period of 18 days with regard to electricity conservation (Foster *et al.*, 2010); the PowerPedia design study—a smartphone-based HEMS that was evaluated with regard to common usability dimensions by 25 participants in a lab setting (Weiss *et al.*, 2012); or the EnergyLife design study—an eco-feedback game that was evaluated in a 5-month field trial by four households and concerned its use and resulting energy conservation effects (Gamberini *et al.*, 2011).

A notable exception from this model of conduct is the design study of EnergyDub—a web-portal based energy monitor that was evaluated in real, long-term use (Erickson *et al.*, 2013). The findings show that in addition to reducing electricity costs and concerns about the environment, curiosity about the technology posed another motivation for system use. They further revealed that credibility and comprehensibility are important design issues. In particular, they argue that it is not enough to simply visualize energy data, but a rich context for interpreting feedback and comparisons is also needed. A similar issue was uncovered by a previous study (Schwartz *et al.*, 2013b) as well as by Neustaedter *et al.* (2013), which suggests the use of calendar information to help users to establish connections between the abstract energy data and domestic life more easily. In respect of the effects of EnergyDub on users, Erickson *et al.* observe that their understanding of the consumption increased, but that the system had only a moderate effect on electricity conservation.

Other long-term studies about using energy monitors in the wild are few but where they exist, they further indicate that initial energy conservation and system usage effects decline over time if dwellers do not change their domestic environment and their habits (Barreto *et al.*, 2013; Van Dam *et al.*, 2010).

Other research is more critical, holding the view that formal models inadequately abstract away from the details of daily life and tend to place technologies in a position of authority over users' lives (Brynjarsdottir *et al.*, 2012). Representative of such a critical stance are the ethnographically oriented studies of Chetty *et al.* (2008), Strengers (2008) and Hargreaves *et al.* (2010). Their findings show that there is no simple cause–effect relationship between feedback and behavioural change as persuasion models propose. They further indicate that energy conservation fails not because home dwellers lack information, but rather because of the complexity and interweaving of household activities (Chetty *et al.*, 2008), people's perception of current domestic practices as being non-negotiable (Strengers, 2008) and 'life being for living' rather than rational decision-making (Hargreaves *et al.*, 2010). Hargreaves *et al.* (2010) further observe that styles of engagement tend to be gender-specific and that domestic energy consumption presents a social and collective rather than individualized process.

We contribute to this research thread by studying the real-life, long-term use of a HEMS in the wild from an appropriation-theoretical stance. This is shaped by the work of De Certeau *et al.* (1980), where appropriation represents the tactics of everyday practice, which give artefacts their individual meaning and results in use, which might be both unforeseeable and unintended.

This stance on appropriation has inspired several researchers to uncover some typical patterns in relation to how people adopt and embed new products in their daily life. For instance, the concept of domestication (Silverstone and Haddon, 1996; Silverstone *et al.*, 1992) stresses that artefacts in a complex and interdependent process have to be made to fit into pre-existing domestic culture and moral economy as well as into local patterns of use and life rhythms. Pantzar (1997) investigates the socio-technological relationship between users and commodities. He further notes that, in the process of appropriation, artefacts move through transformations of meaning, leading from initial phases of exploration and excitement to—eventually—the routine. Integration of technology into existing functional needs, or desires brought about by the artefact itself is critical for the long-term usage of technology. Stewart (2003) also uncovers some common themes concerning domestication such as privacy, family/well-being, communication, etc. He further outlines that in order to understand consumption we have to take into account the social processes that are shaped by background and personal history, events, activities and by the social network.

The openness of the appropriation process has a methodological consequence insofar as the research question is reversed. Rather than asking what technologies do to people, we ask what people do with technologies. To uncover local rationalities, meaning and practice, it implies that appropriation studies need to be qualitative and ethnographical in nature (Chaiklin and Lave, 1996; Pierce *et al.*, 2011). In particular, the categories that we use to describe these phenomena need to be emergent. Appropriation studies, in this view, should not be predicated on existing theories or perspectives, but should be methodologically indifferent (in the sense in which Garfinkel (1967) uses the term). Existing work on domestication and using energy monitors in the wild, then, is of great heuristic value, but does not exempt us from the duty to develop categories from within a particular case.

To understand what energy monitors mean in the everyday life of people, we follow this view on appropriation by using a grounded theory approach (Glaser and Strauss, 1967) where existing literature sensitizes, but does not determine our analysis.

3. RESEARCH DESIGN

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 HEMSs. To address the complexity and situatedness of HEMS use in real-life environments, we applied a living lab approach (Bernhaupt *et al.*, 2008; Eriksson *et al.*, 2005; Følstad, 2008). Living labs make it possible to bring users and technology together in an open-ended design process in real-life environments (Følstad, 2008). They specifically support long-term cooperation, co-design and collaborative exploration among researchers, users and other relevant stakeholders. Involving users in the design process from the very beginning for 'sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts' allows a continuous formative evaluation of the designed artefacts and uncover appropriation phenomena at early stages of the technology life cycle (Bernhaupt *et al.*, 2008).

At the beginning of our living lab set-up (cf. Fig. 1), we conducted a *pilot study* (Schwartz *et al.*, 2013b), between November 2009 and May 2010, with an independent set of

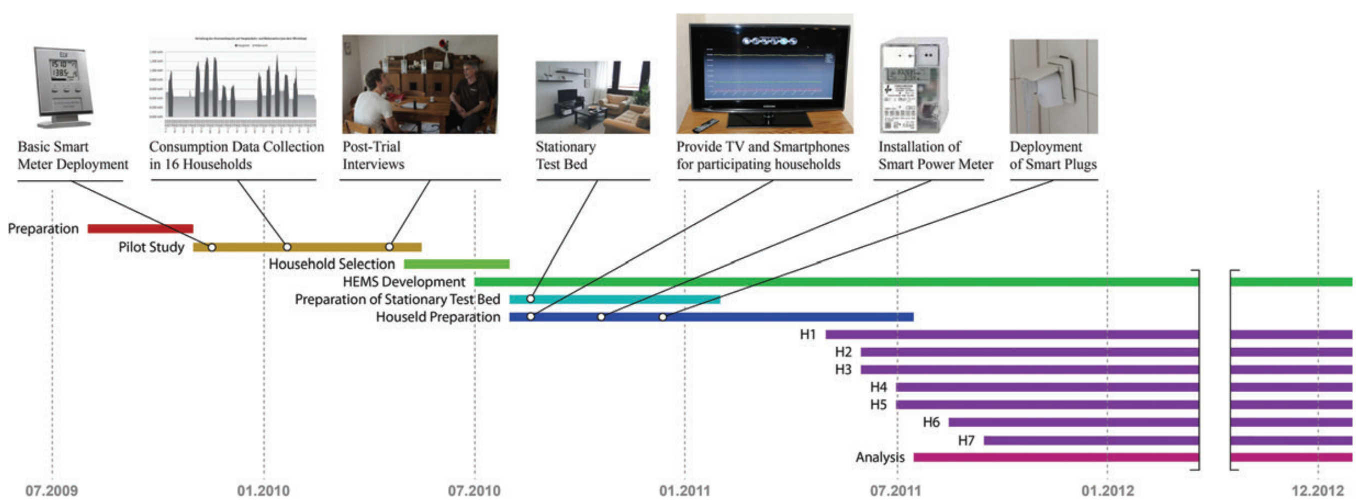


FIGURE 1. Research Design.

TABLE 1. List of households.

Type of flat	m^2	Type of household	Participants	Sensors	Equipment provided with project
RA	69	Couple	Female, 27, Teacher male, 26, Office Clerk	SmartPlugs	Flatscreen TV, Smartphone, Media Center PC
RA	80	Couple	Female, 28, Marketing Specialist male, 31, PhD Student	SmartPlugs	Flatscreen TV, Smartphone, Media Center PC
OFH	140	Family	Female, 37, Office Assistant male, 39, IT Specialist	SmartPowerMeter, SmartPlugs	Flatscreen TV, Smartphone, Media Center PC
OFH	120	Single	Male, 44, Banker	SmartPowerMeter, SmartPlugs	Flatscreen TV, Smartphone, Media Center PC
OFH	145	Family	Female, 60, Office Clerk (part-time) male, 66, Retiree male, 28, College Student	SmartPowerMeter, SmartPlugs	Flatscreen TV, Smartphone, Media Center PC
OFH	140	Family	Female, 45, Housewife male, 47, Mechanic female, 10, Student female, 7, Student female, 5, Student	SmartPowerMeter, SmartPlugs	Flatscreen TV, Smartphone, Media Center PC
RA	55	Single	Female, 29, PhD Student	SmartPowerMeter, SmartPlugs	Flatscreen TV, Smartphone, Media Center PC

RA, rented apartment; OFH, one family house.

households with 46 participants in 16 homes. We provided an out-of-the-box smart meter infrastructure that measured energy consumption on an appliance level over a period of 10–15 days. While participation was voluntary, selected households varied widely in demographics (age, gender), living arrangements (home owner, apartments) and in terms of social and professional backgrounds. Following device-testing and data acquisition, we used the collected consumption information for conducting workshops in the households where we launched informal and unstructured discussions about practices and preferences. All workshops were audio-recorded and to large extent videotaped as well. We analysed the data using media annotation tools in an open coding fashion, to look for common patterns and categories related to the ways how people make use of consumption feedback and how they relate to and live with such a system. We explored existing energy practices, sense-making strategies and accounting procedures for consumption with our partners, drawing on metering information and empirical data we had thus far collected.

In the next step, we conducted a longitudinal living lab study, based on a qualitative sample of households which we chose following a comprehensive selection process. The sample was obtained, in the first place, by placing information about the study in the local press and via radio stations. Interested people were asked to submit an online questionnaire with basic information concerning their households' infrastructure, motivation for participation and expectations about the project. Additionally, telephone and on-site interviews were conducted to gather additional information about the households, including technological constraints and prerequisites, such as the availability of Wi-Fi and the possibility of installing smart meters and device-level meters. We finally selected seven homes with 16 participants. An overview of the selected households and of the participating members is provided in Table 1. All households were located near the city of Siegen, Germany, representing a typical sample for this region (Federal Statistical Office Germany, 2011). This sample size allowed us to include a range of different household settings and, within the project's resource limitations, to distribute an entire HEMS system including a set of interactive devices. With a planned overall research period of 24 months, the sample was expected to produce a large body of data that would allow for an in-depth analysis. As can be seen in Table 1, households ranged from one to five in the number of inhabitants and from five to 66 in age. Furthermore, different levels in terms of technological skills and knowledge as well as educational attainment were included. Motivation varied, stemming from disaffection with current energy billings, technological interest and curiosity about being part of a research endeavour. While all participants reportedly had a high general interest in saving energy, only H5 had taken action in taking sample measurements of appliances and calculating their total impact on the annual bill.

For our initial *HEMS development*, our design was based on empirical analysis of our pilot study and, to a limited extent, on usability features gleaned from the literature on consumption feedback design. The technical HEMS set-up consisted of a number of different components.

First, capturing the households' overall power consumption required replacing the existing mechanical power meters with digital *SmartPowerMeters* that enable capturing the overall energy consumption of the respective household. Once installed, we were able to receive measurements via 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 participant's home network. During the operation, the meters continuously sent out consumption data using *SmartMessageLanguage* protocol via message push (VDE, 2010).

Secondly, in order to capture power consumption on an appliance level, *SmartPlug* sensors were used providing disaggregated measurements. The *SmartPlugs* can easily be installed by plugging them between the power socket and the appliance plug. Using an autonomous Zig Bee network, they provide information about current power consumption and keep a history log of energy consumption of connected appliances. Additionally, the hardware allows turning appliances on and off remotely.

Thirdly, the HEMS included a Media Centre PC, which we connected to the households' main TV. This computer acts as a *SmartEnergyServer*, managing, storing and processing measurements. The server also runs the HEMS' *EnergyMonitor* software to feed back a graphical user interface visualizing collected information. The software was designed in a way that allowed for a straightforward interaction which did not require any prior knowledge or special training. The system has been iteratively developed throughout the project, predicated on participants' feedback and our observations. In its current version, the *EnergyMonitor* includes seven screens that show readings from the *SmartPowerMeter*, information on real-time power consumption, an energy consumption history log and a comparative tag cloud. The latter allows users to freely assign tags to *SmartPlugs*, thus grouping them according to personal preferences. Selected views of the *EnergyMonitor* are shown in Fig. 2.

Fourthly, when interacting with the *EnergyMonitor*, users were able to access feedback from a common interface when calling the *EnergyMonitor* from their TV, computer, tablet device or smartphone (cf. Fig. 3). In the case where households were not equipped with a TV or smartphone, relevant hardware was provided.

Once selected, significant effort went into the *preparation of households*. Since technological conditions and premises varied considerably, we needed to standardize participants' infrastructure in order to create equal basic conditions for our HEMS throughout the entire project. For installing the *SmartPowerMeter*, the support of respective electricity providers was required. Previously, we had analysed the technical features of different Smart Meters, to assess the implementation costs of communication protocols and facilities for our HEMS prototype. The deployment of the *SmartPlugs* was carried out during collaborative workshops with householders and our project team. We conducted a deployment workshop with each household, during which they distributed the *SmartPlugs* in their household. Participants were free to position them, limited only by the necessity of a working Zig Bee connection. Within each household, about 10 *SmartPlugs* were deployed (Overall, 72 *SmartPlugs* in 7 households). Every deployment was documented in terms of type of appliance, usage context, position in the house, person who wanted to have it there and a short indication of reason. Figure 4 illustrates how people deployed the *SmartPlugs* within their homes.

Additionally, we implemented a second, *stationary control test bed* in our lab. This test bed was equipped in a similar way to the participants' households in terms of technology. Hence, we were able to run tests under similar conditions and eliminate technological problems before rolling out a new HEMS version.

After this initial work, 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 motivation affecting energy consumption. The questions of the initial interviews focused on participants' management of electricity consumption at home. From this time onwards, numerous activities within the participating households were conducted, including in-depth interviews, prototype explorations, user workshops and participatory observations of the use of the *EnergyMonitor*. We frequently visited the households, supported them with technical problems and provided new versions of the HEMS when available. The focus of our investigations evolved and varied slightly over time. While at the beginning questions centred on current management of electrical consumption and attitudes towards resource consumption, we then shifted towards more detailed questions about HEMS use in participants' daily life. Also, occasional workshops included more specific tasks such as usability testing and design sessions.

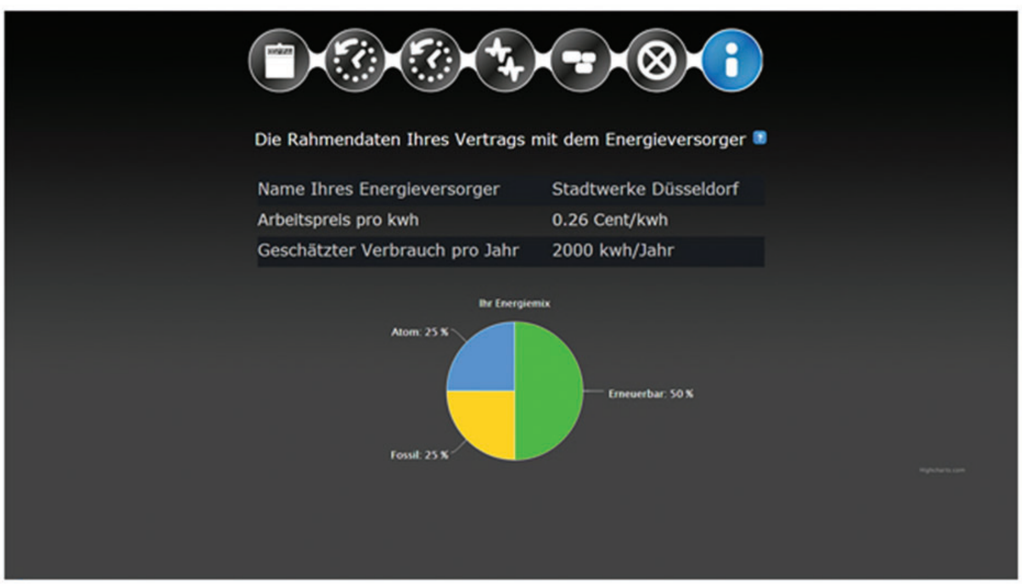
For *data collection*, our research involved a mixed-method approach with a view to triangulating the results (Flick, 2009).

As our first source for unobtrusively collecting data in real-life settings, we studied the integration of HEMS into the local context and its use over time, by evaluating the log files of the *SmartEnergyServer*.

Secondly, for validating usability and assessing the level of acceptance of our HEMS design, we conducted an AttrakDiff survey (Hassenzahl, 2006) to learn about the perceived usefulness and easy use, as well as hedonic and pragmatic qualities (Davis, 1989; Hassenzahl, 2006). The survey conducted showed the level of acceptance and pointed out that the system was perceived as both usable and attractive.

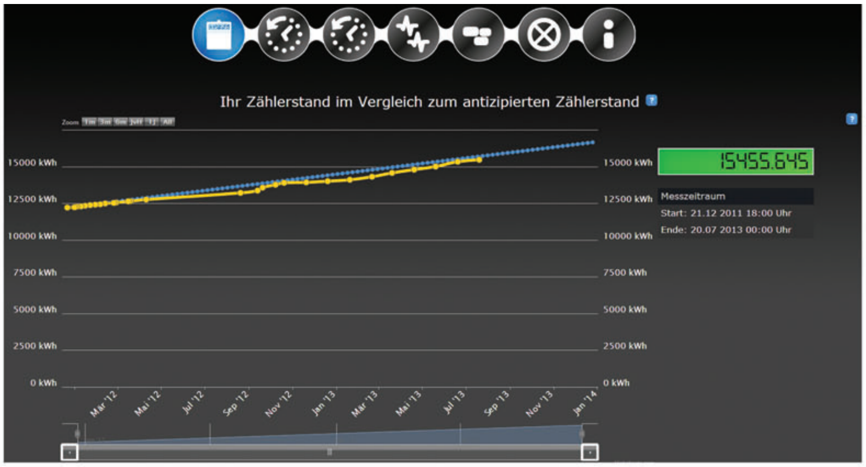
Thirdly, to understand the households' dynamics (Hargreaves *et al.*, 2010, 2013; Wallenborn *et al.*, 2011), we studied emerging practices and critical incidents (Stevens, 2009). Here, we relied on qualitative data captured during interviews, informal talks and observations from on-site visits. Overall, we audiotaped 70 interviews and 34 workshops, with a total length of over 200 hours. Several million datasets on the energy consumption of

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

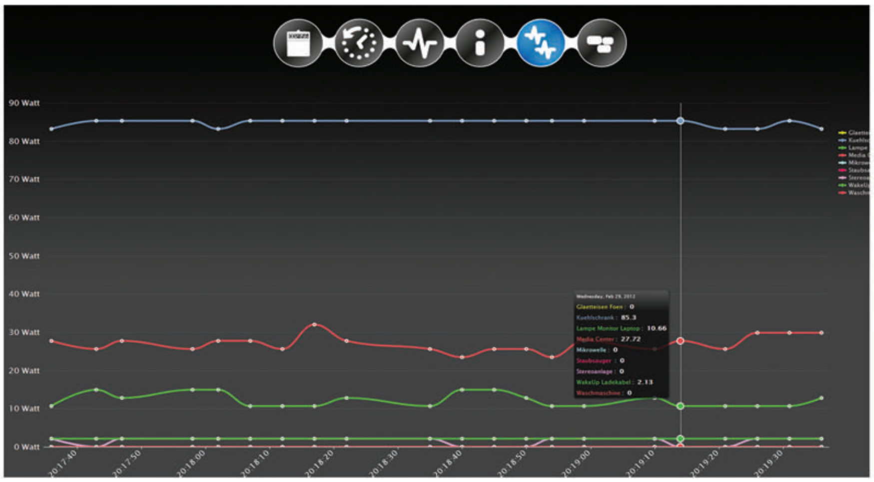


Contract Information: This screen shows the estimated consumption for the current year, based on last years' consumption, the utility providers' name, the price per kilowatt hour, and the composition of the energy mix.

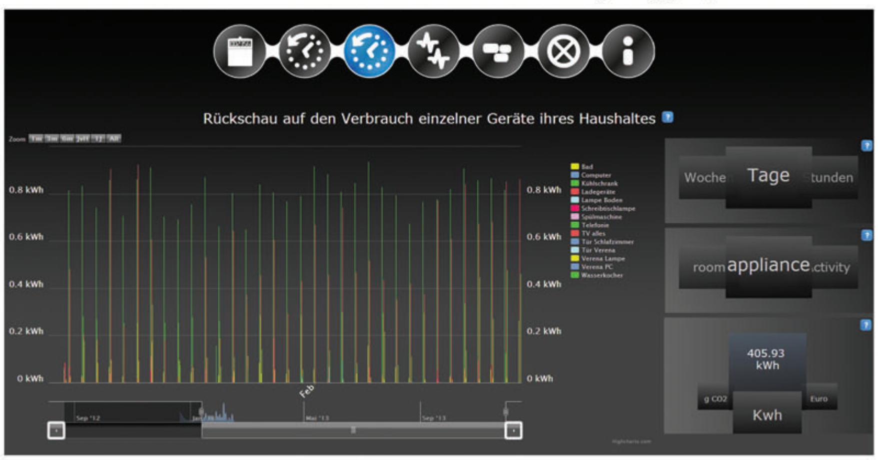
FIGURE 2. Main views of the Energy Monitor (realized as HTML pages that could be displayed on Television, Smartphones and Computers).



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 a real-time visualization of the current power usage, measured by the *SmartPlugs* and the *SmartPowerMeter*. The visualization can be filtered according to tag groups



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

FIGURE 2. Continued.

households and appliances were gathered over a time span of 18 months.

Furthermore, households increasingly accepted remote access to the *SmartEnergyServer* even in their own absence, which was helpful when installing new releases or preparing follow-up visits and observing the usage of new features.

As we have suggested, most research into domestic energy consumption has focused on feedback mechanisms and how they affect individual decision-making. Our concern is rather different and, as such, the development of alternative concepts is a part of our focus. For this reason, we chose an inductive strategy. Grounded theory, of course, has been subject to a number of criticisms and various interpretations. They range from the earliest formulations, associated with Glaser and Strauss (1967), through separate inputs from Strauss and Corbin (e.g. Strauss and Corbin, 1997) and from Glaser (1998) and more 'method oriented' treatments associated with Charmaz (2006).

For our *analysis* of the collected data, we followed an open coding process and the constant comparative method as suggested by Glaser and Strauss (1967). To explore the impacts of our HEMS on domestic life, we analysed the data from on-site interviews and workshops using an open-coding process, as suggested by grounded theory (Strauss and Corbin, 1997). After each step, the transcripts of the material were scrutinized and coded. Therefore, we used software tools to analyse and tag the text-based transcripts of the conducted interviews to identify similarities in using HEMS among the different households. At first, we composed categories based on the findings in the collected data. Then, these categories were related to each other (axially coded) and evolved through further research and investigation steps. As is typical for a Grounded Theory Approach, data collection, analysis and interpretation were intertwined and newer data were constantly compared and included into already assembled codes. This analysis provided the foundation to generate the categories presented in the next sections.

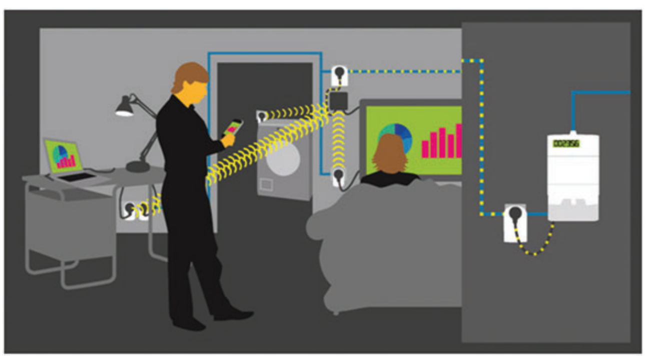


FIGURE 3. Collect consumption data on a central home server and provide multiple accesses to get feedback on different devices.

4. IMPACTS OF HEMS ON DOMESTIC LIFE

In this chapter, we will present the results of the open-coding process of the collected data. Our analysis resulted in nine categories, which we will describe in the following. Each category begins with a title that describes the core aspect of the category. We will then summarize the category in a short paragraph, before describing it in more detail, supported by empirical results.

4.1. We are curious

Our participants were highly motivated to investigate their domestic energy use with HEMS. Once they discovered the opportunities provided by the technology, they are keen to monitor their domestic energy use. Participants named *real-time local information of energy consumption* at point-of-use as the most important benefit. The new possibilities provided by the HEMS starkly contrasted with their past situation, where consumption had remained largely invisible.

Our study shows the value to households of having a controlling instrument at hand, one which monitors their consumption and enhances energy awareness. Within the conducted AttrakDiff questionnaire, the hedonic quality stimulation (HQ-S) is rated high (mean: 1.6). This value addresses the human need for excitement (novelty/change) and refers to quality aspects such as 'innovative', 'exciting' and 'exclusive' (Hassenzahl, 2006; Fig. 5).

FIGURE 4. Deployment and documentation of SmartPlugs within collaborative workshops.

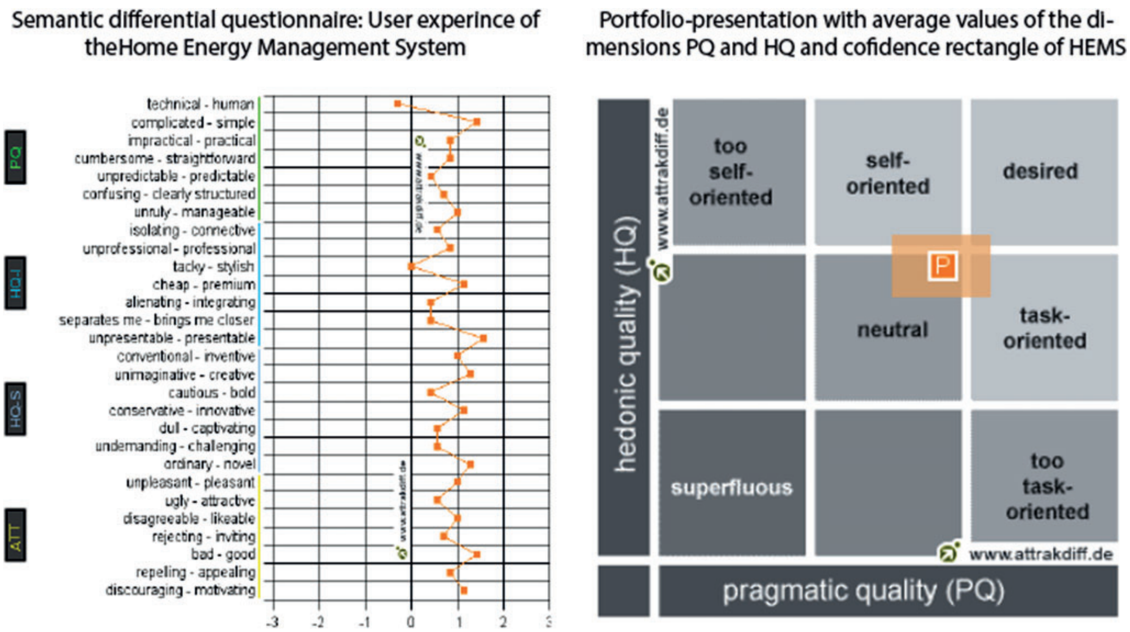


FIGURE 5. Results of the AttrakDiff questionnaire.

The following examples show how participants manifested their interest in using the system to observe their energy consumption and get a detailed picture of their local energy system:

Example 1

Interviewer: *So, if you could say again, on a general level, what was good and what wasn't. Can you give us feedback?*

P1: *I thought it was really good, that you could measure every appliance. Even if I was charging my mobile phone or something else, I could measure that. That's also interesting in regards to something being on stand-by, let's just say, using 100 W. How is it used? I have an overview over all of the electricity I use. Before I would have had to do that manually and now I can see it on the display. I like that. That is very useful, because I can see where electricity is being used and how much is being used.*

Example 2

Interviewer: *What are your experiences with the smart metering system that we installed? How did you use the system? […]*

P2: *Yes, I have to say, the whole thing interested me from the start […] so I did look at it, I was really curious […] my wife was vacuuming and I took a look to see how much [electricity] the vacuum cleaner uses.*

Example 3

P3: *So, it was always interesting [using the system], I turned on the TV and then I saw how much energy the different appliances consume by comparing it to what it was before. That was pretty interesting—'guys, tell me what you've switched on'—so that I can keep track of what they're using [...] and that's how it was, then you can compare the days, my wife was doing the laundry, so the usage is higher and so on. That's pretty interesting.*

Example 4

P4: *Well, I said: I thought maybe you switched on a device or your laptop, because the curve is up to 200 W, but I don't know why. Then I thought, maybe it's the fridge because it cools now and then but then it showed 100 W before and I don't know which device needs 60 W, that means the 40 W that the PC uses plus the 60 W […] I have to check this again, that's very interesting, clearly!*

The ability to get immediate consumption information was the most attractive aspect of using the HEMS in the participating households and was mentioned as 'most beneficial' and a 'quick win'. The system log files show that 'real time power information' was the most used page of the HEMS. The current meter count ('meter information') (Fig. 6) ended up as second most positively received information.

We found how options for monitoring and inquiring consumption were directly connected to the means of measuring consumption by deploying the sensing infrastructure. Participants frequently reflected on how to deploy smart plugs in order

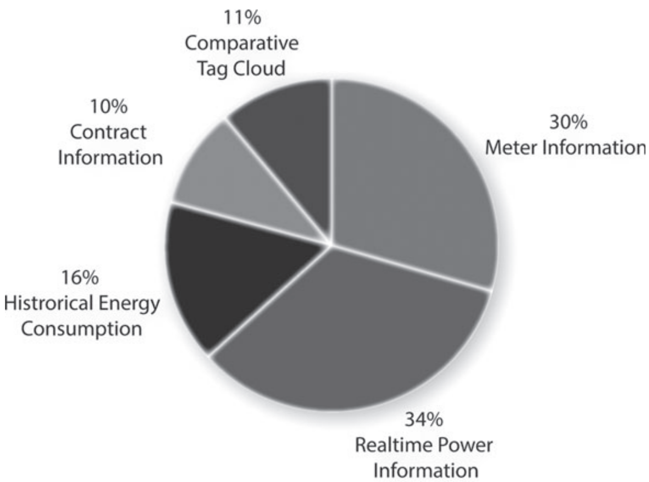


FIGURE 6. Overview of HEMS component usage.

to get the most interesting information from their local energy system.

This includes both the aspect of *coverage* of consumption information from single devices and the aspect of *granularity* for a detailed view on domestic consumption.

During the initial phase of HEMS deployment, participants mentioned that it was important to them to include all major appliances, so that the overall energy picture was as complete as possible, despite the limited number of *SmartPlugs*. Householders consciously positioned the *SmartPlugs* within their homes according to their own preferences and needs. We noted some recurring decision-making criteria across households. Participants repeatedly reflected on their most frequently used appliances and devices that they believed use a lot of energy and matched this with *SmartPlug* distribution. Figure 7 gives an overview of the devices distributed within the homes, summarized per device category and the coverage of the total household consumption. In nearly every household the initial deployment of *SmartPlugs* was changed during the time of our study to improve the coverage and to accommodate individual preferences in monitoring consumption.

4.2. I or we

Using the HEMS influenced social relations and interactions between household members. There are two broadly distinct cases of HEMS use: Either one person is the main and independent HEMS user or HEMS is used in a more social, collective fashion.

From our data, we identified two different types of HEMS use: On the one hand the *local single energy expert*, and on the other hand householders' collaborative and mutually elaborated use of the HEMS.

With the first type, the prevailing user takes on the role of the local energy expert who is in charge of the topic of domestic energy usage for the entire household. In households with multiple members, this person was our first contact and simultaneously the energy expert in the home, as the following excerpt shows:

> ***Interviewer****: And did you check it together with your wife?*

> ***P5****: Yes, sometimes, but I am the one [who uses the system]. She of course found that interesting, too, but technical stuff is my business, she probably wouldn't even know how to boot it [HEMS] up.*

Here, we also observed in some cases that family members asked their 'energy expert' questions concerning consumption. The expert then either gave advice or supported the use of the HEMS.

> ***P5****: She asks me and then I said: 'Here you can see how much the washing machine consumes or how much the dryer consumes…*

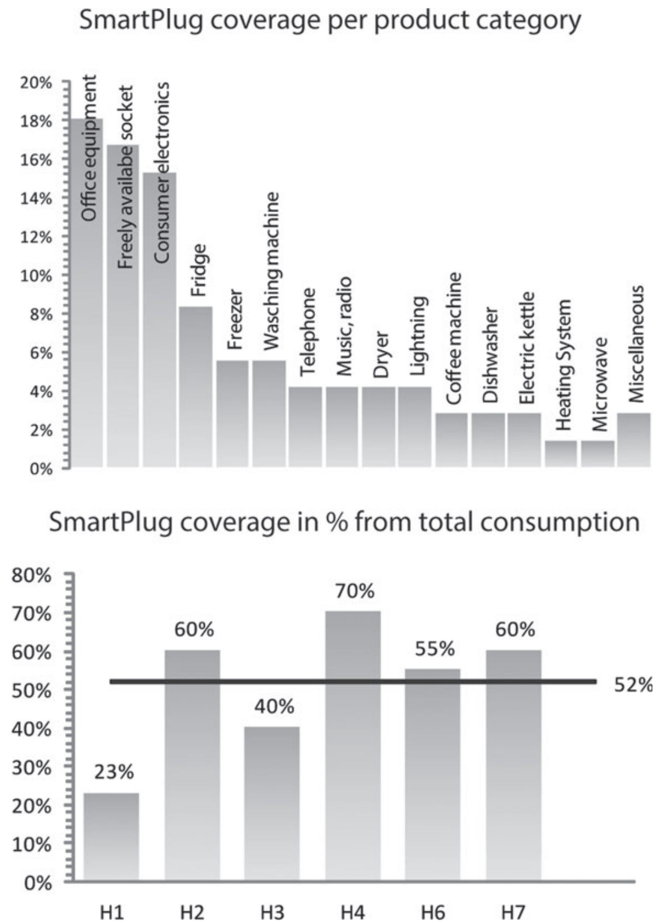


FIGURE 7. Overview of device categories covered by Smart Plugs and coverage by Smart Plugs from total in %.

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

> ***P6***: *Yes, now I know that my daughter used the computer and listened to music at the same time and she also was on the phone and went outside to the balcony for a phone call. And then I just said: Hey, there are already 100 W from your room alone. Either you switch off the devices or you hang up. That's a thing: phone calls with the teenagers these days go on for half an hour or an hour and the devices are on anyways.*

Here, the social interaction between household members is about advice and attempts by the local energy expert to avoid an inefficient use of resources.

In the second type of use, householders develop mutual practices to understand their energy use. Householders use the HEMS collaboratively and mutually develop strategies for optimization. Here, for instance, one person would monitor the HEMS on the TV, while the other person would walk around the house to turn appliances on and off.

> ***P7***: *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, to see how that shows up on the curve. Or when she intentionally went downstairs and then turned on the washing machine, we could track the impact.*

We observed that a collaborative use of the HEMS influenced social relations and interaction between household members. In the case of multi-person households especially, the use of the HEMS triggered communication among members. This included an increase in decision-making and coordination processes among the members of the household concerning their energy usage. We observed recurring forms of communication where sharing experiences and joint optimization played an important part. This form of exchange mostly aimed at the promotion of collective efforts to optimize and control the current state of energy use within the homes. The following quote is an example where a husband mentioned how he communicated spontaneously whilst at work with his wife at home, in order to clarify energy use at home:

> ***P8***: *When we did this I could not understand one thing, and that's when I remotely logged in [from work], when I logged in it was about 100 W. Well, I thought, that's the computer itself, but wait, that is only 40 W. So I thought, OK, maybe there are some other appliances running. But then the curve goes up to 200 W—and I think 'what?' there's nothing else switched on at home. Then I called my wife at work or on her cell and asked: 'Did you just come home? Because she goes home at lunch time'. She says: 'No, I'm at work'.*

In these cases where the HEMS is used collectively, forms of communication are shaped by the goal to develop a common understanding of energy usage within the homes to achieve energy consumption optimization through joint efforts.

4.3. Energy literate[1]

The HEMS fosters learning about electricity consumption and ascribing a meaning to the information presented by it. They become more literate and thereby much more specific and expressive in talking about their home energy usage.

This theme became visible in the stark contrast between the interviews before HEMS installation and after. We will use the following two parts, taken from interviews with the same person from household 2, as an example of the growth of knowledge and the capabilities of householders regarding their individual energy literacy. The first excerpt is taken from the first visit in 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.

> ***P9***: *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 (cf. Fig. 8).

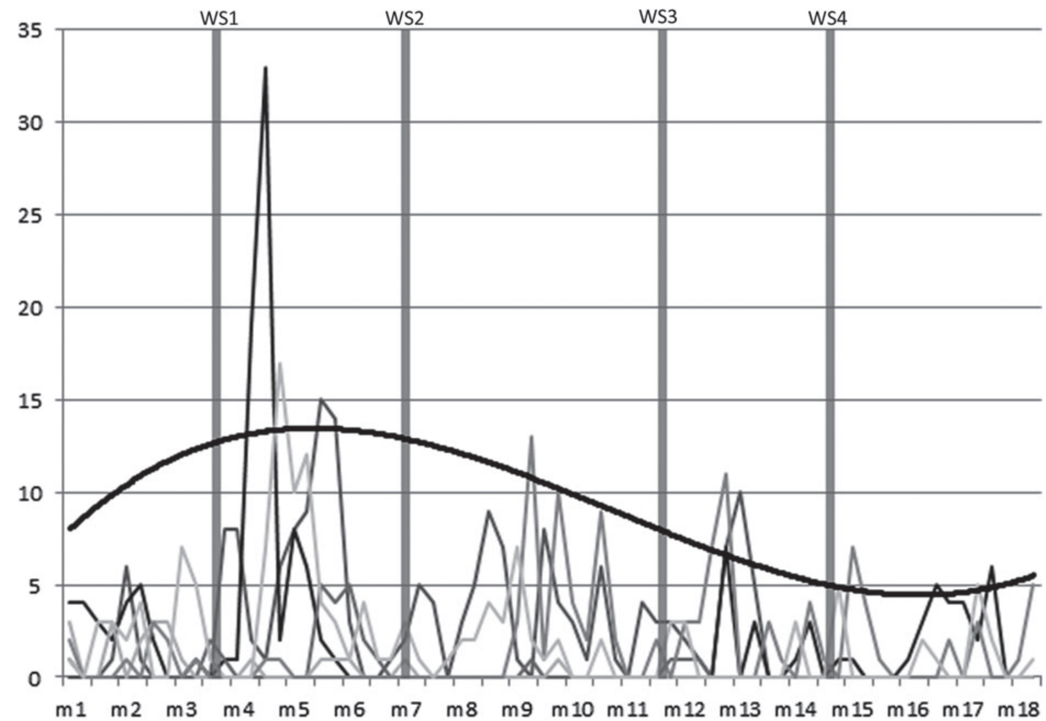
> ***P10***: *[it was beneficial] seeing how much each device consumes and then to think about it […] Alarming how much we use in the evening. […] The TV consumes quite a lot, I have to say, almost 600 W [...] and when the oven rockets up to 3000 W […] And the dryer, I would have said it needs quite a bit, but the consumption actually was not that high. I thought it goes up to 2000 W or so […] if it does full heat. But then it was only 400 W.*

Here, the participant is able to de-aggregate his individual consumption on an appliance 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 competence to assess his own 'energy system' seems to have grown through the use of the HEMS.

This was a common observation in all participating households. Throughout the study, householders increasingly mastered the drawing of a detailed picture of their local energy system after using the HEMS. Participants were able to be quite

[1] A detailed report of this category can be found in (Schwartz et al., 2013a).



	Days of Exploration	HEMS access total per household	Average access per day	Average access every X days
H1	536	177	0.33	3.03
H2	490	160	0.41	2.43
H3	487	139	0.29	3.50
H4	501	141	0.28	3.55
H5	247	21	0.09	11.76
H6	501	113	0.23	4.43
H7	316	25	0.08	12.64
	∑ 3078	∑ 818	Ø 0.24	Ø 5.91

FIGURE 8. Usage statistic based on log file analysis of the HEMS system.

specific about consumption data relating to their appliances and demonstrated this by using numerical units of consumption in their descriptions.

We observed that Energy Literacy, for our respondents, presents a value in itself. It had a significant influence on covering and improving both the general and theoretical knowledge about energy, as well as promoting the skills necessary to understand one's 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 that we observed was an evolving process with the accurate and trustworthy information on energy consumption and the reflexive contextualization of this information mutually informing what participants had to say. Participants progressively made a connection between energy consumption information and the context of their daily life. This connection represented an important precondition for an informed reflection about the actions that may lead to significant changes in consumption patterns.

4.4. We are proud

Householders identify with the system. They proudly present the HEMS to their friends when they visit and also remotely from work to their colleagues.

As reflected in the peak value of the AttrakDiff evaluation, HEMS users think that the system is highly 'presentable' (Mean: 1.7). This is related to the system's hedonic quality identity, which refers to human needs like pride, social power or status (Hassenzahl, 2006).

Our users often expressed the view that they liked the system and could identify themselves with it. As the following statement shows, they also presented the HEMS system to others:

Example 1

Interviewer*: You said that you used HEMS a number of times. How did you like it? What did you do with it?*

P11*: Also, if friends came over, I say: 'Look here [and they would say]. What did you have here? That's cool.' Then I said: 'Hold on. Then I turned on the heater and when it jumped to 3000 W […] you see it's going up and down.'*

Interviewer*: So you showed it to other people?*

P11*: Yes, of course also from home. Or I dialled in and then showed a colleague: 'Here, look at this! You can see the current power consumption.' 'Oh yeah, that's cool!' And then he would say: 'Oh, I would have liked that too …'*

Example 2

Interviewer*: And did you sit together and look at it [you and your wife]?*

P12*: Yes, […] also when there were visitors, we showed it.*

Given these viral effects, we received requests from other people asking if they could become participants of our study too and we currently keep a list of users to take part in a future project. More importantly, and although we have limited data as yet, these results provide some early indication of a wider network effect that has been hitherto unreported. Our evidence suggests that user pride in the system and their developing abilities to monitor and understand information provided have some spillover influence outside of the family.

4.5. Maintaining the overview

The HEMS allows participants to make their energy consumption visible, a fact that they consider very beneficial. Beyond an initial curiosity (4.1), there is a sustained desire to maintain an overall picture and monitoring accurate control of energy usage at home.

The need for maintaining an overview increases with time, as HEMS use changes from a 'single point investigation tool' to a control system, which continuously relates information in a broader context. We observed that our users continuously used the HEMS to maintain an overview by checking the plausibility of their energy use from time to time, as the following example shows:

Interviewer*: That means you sit here and check it from time to time?*

P13*: Yes, yes, exactly. It is the interesting to see it again. You know in principle everything is alright. If then suddenly it goes up to 2000 W … well maybe someone is stealing power or there's a malfunction in the house or so.*

At an early stage in the project, a recurring pattern was that participants roughly estimated their consumption based on verifiable values and plausible reference scenarios (as shown in the above quote). Given that householders were increasingly able to draw a detailed picture of their energy system over time, this allowed them to maintain an overview of consumption. Checking the plausibility of consumption posed a similar motivation for using the HEMS continuously. The practices of estimating and comparing consumption steadily developed. Previous values and more detailed reference scenarios become increasingly relevant as the following example shows.

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

P14*: […] 300 Watt, currently, for mid-day is not so much. Usually we have 500 Watt … I memorized this because I check continuously.*

The aspect of keeping energy use under control is also visible in the log files. Users frequently accessed the system right from the beginning and sustained their usage behaviour over time throughout the 18-month period of our study.

Overall, the analysis of the log files show that users accessed the HEMS on average every 5.9 days (range: 2.43–12.64) to check their domestic energy consumption. Small peaks in use became apparent after conducting major project workshops (WS1: deploying *SmartPlugs*; WS2: Software Release Version 2; WS3: Software Release version 3; WS4: Evaluation). Use, however, also continued more or less stably without any project-related interventions.

Our finding of a sustained use points to the wish of users to maintain an overview of energy consumption and control impact of actions taken or developments in general on a longer term. Even though usage statistics in some cases show a decline in HEMS access over time, at the same time it clearly demonstrates an overall usage beyond an initial interest. Our iterative design process, one which successively provided households with more sophisticated HEMS interfaces, might have fostered interest and motivated participants in learning about their energy consumption.

4.6. Individual accounting

Ways of explaining private energy consumption are highly individual. The adaptability of our HEMS made it possible to include individually defined metrics and individual definitions of comparable groups and classes. With this support for adaptability, users could progressively create a feedback system that displays consumption in a language that is meaningful to them, and that better captures different reference systems for specific situations.

Our study shows a multitude of different ways of talking about energy consumption in terms of categories that are meaningful to users. People use different mechanisms that relate to their individual context to make their own energy use accountable and explainable, as exemplified below.

> ***Interviewer****: What is electricity for you?*
>
> ***P15****: Electricity to me is what I use. When I drink a cup of coffee, I know that I'll spend that much for that. Electricity to me is also not measurable. That's the problem I have with it. I can't really explain that to my kids: ‚Look, you're using electricity now.' They'll just say ‚Why? I'm just listening to music, I'm not using electricity.' Those are things that are really hard to explain.*

With this in mind we designed HEMS to have a potential for flexible adaptation in order that it may addresses people's individual approaches to making consumption visible and accountable. As we had already identified this issue in our pre-study, we integrated a tagging mechanism that allowed flexible methods of structuring, categorizing and displaying measured values. This mechanism allows them to generate preferred views and makes it possible to include individually defined metrics or to redefine comparable groups and classes. With the help of user-defined tags, users could progressively create a feedback system that displayed consumption in their own language. This customization affects the form of visualization of measured data visible on the screens ‘Comparative Tag Cloud’ and ‘Real-Time Power Information’ (e.g. Fig. 9).

We observed that users often found this feature very helpful, especially when making comparative estimations.

> ***Interviewer****: Looking back, what went well, what was bad? Is there anything special that you recognized?*
>
> ***P16****: Yes, well, yes. What I especially noticed is these customization options [...] they were really useful. That's where you could put things next to each other and you can concentrate on what you're interested in, especially in the live view, but also in the other views.*

Most of this adaptation took place at the beginning of the HEMS exploration phase. Here, the definition of clusters of devices was often mapped to ways of consuming them as services. ‘Being in the living room’, for instance, was a service that participants wanted to understand and which often became a reference for further analysing and estimating household consumption. It also became apparent that emerging skills (cf. 4.3) influenced clustering policies. Over time, participants suggested redefining clustering in terms, for instance, of ‘always on’ devices versus ‘activity based consumption’ or alternatively consumption data structured by ‘persons’ or ‘activity’. The service, ‘watching TV’, for instance, could include the appliances TV, stereo amplifier, receiver and DVD player.

The wish to group domestic energy consumption by the category ‘persons’ was expressed early on in 4 cases. But households discovered that they found it difficult to clearly assign consumption to an individual person and therefore discarded the idea. Overall, we see the grouping of devices and consumption into meaningful, individual categories, as a key requirement for HEMS design.

4.7. Embedded in daily life

HEMS usage became part of daily routines and was a sustained activity throughout the study. The TV became the main device to access the HEMS as it allows for a seamless integration with existing practice.

In our study, users had the option to access the HEMS from a variety of home media devices, including TV, smartphones and (in two households) via a tablet computer (Fig. 10).

Where smartphones were present in the households, we found that accessing the HEMS via smart phone accounted for only 2% of access occasions. In households where a tablet PC was at hand, it was used only for 6% of HEMS access.

Analysing how people accessed consumption information throughout the study showed that the access of the HEMS by TV prevails. Users frequently checked their current energy consumption before or after watching TV or during commercial breaks.

> ***Interviewer****: And did you have special occasions to check [HEMS]?*
>
> ***P17****: No, just spontaneously, when I watched TV. If the TV was on anyways, then I'd turn on the system [switched to EnergyMonitor] in the background. So, not always, but especially then.*

The sustained use of the HEMS that we described before was clearly linked to the already existing practice of watching TV and the available free time during commercial breaks. The integration of the HEMS into daily routines, thus, is an important factor for sustainable use.

To an extent, we must speculate about why this is so. Clearly, television is a major part of daily life, and moreover one of those occasions in family life where more than one family member might be present. If it is the case, as we hypothesize that it might be, that mobile phones and tablets entail more private use, then this could be explanation. Otherwise, it might be an artefact of the amount of continuous time spent in front of the television. It does seem that ‘natural breaks’ in TV consumption are associated with HEMS monitoring.

4.8. Losing trust

Misleading or misinterpreted data provides significant challenge to householders and is a reason for questioning the overall

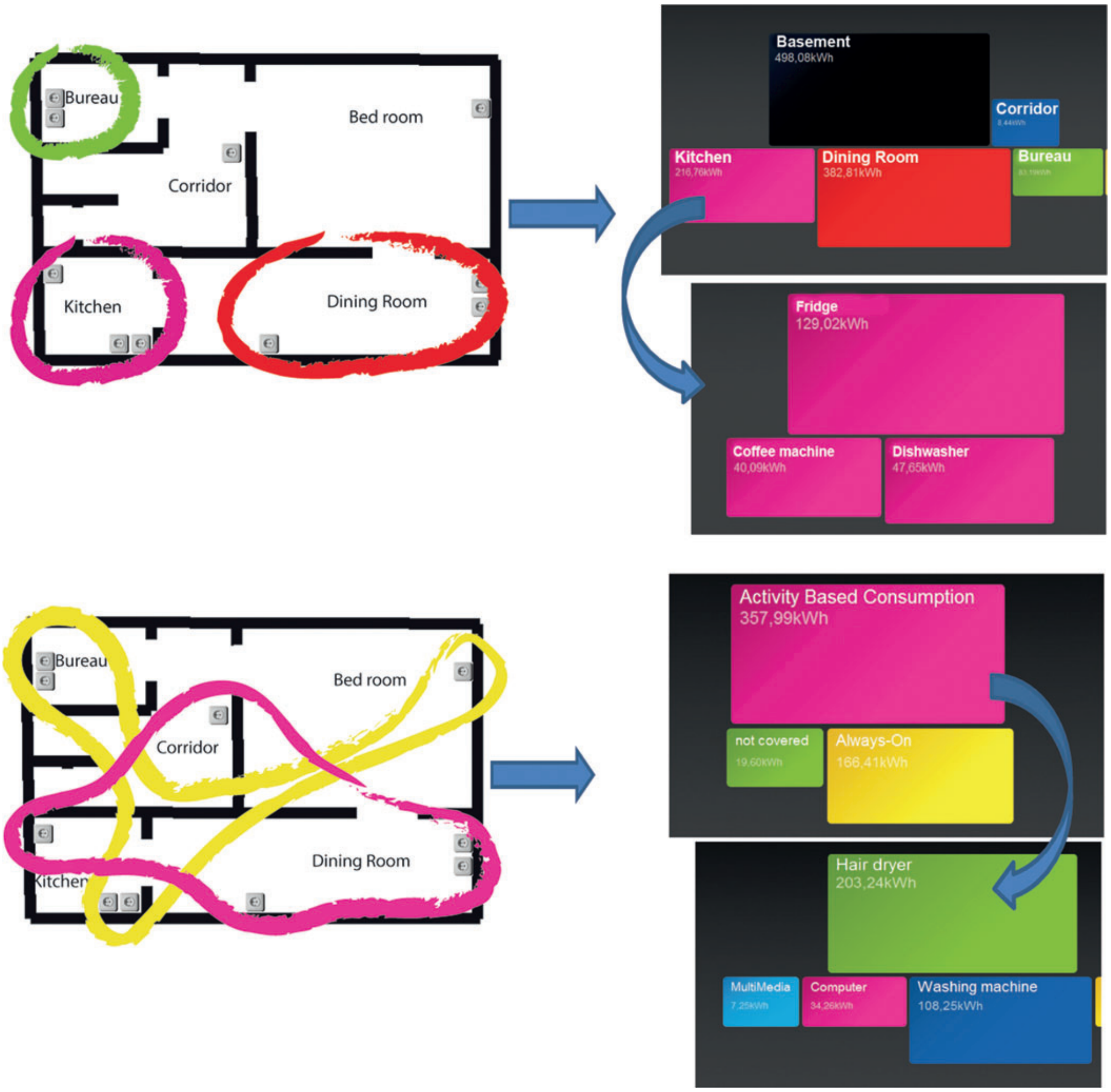


FIGURE 9. Consumption data structured by ‘rooms’ (top), consumption data structured by category ‘always on’ (below).

FIGURE 10. Providing Energy Feedback on multiple devices within the home.

value of the system in question. We observed that regardless of the underlying reason, information that is not immediately plausible makes users question the entire system and the value of additional information.

In situations where participants were sceptical about information provided by the HEMS (which in most cases was caused by a lack of personal knowledge on how to analyse a specific situation), they tended to generalize about the overall reliability of the system. For our participants, the plausibility of the data presented is a matter of high priority, as shown in the following example.

> ***Interviewer****: How did it go, with the system? Do you remember when you used it for the last time?*

> ***P18****: […] Sometimes, values for me were not immediately evident […] and somehow, I believe they were not always displayed correctly […] so I really rather kept my hands off it. It did not make sense for me anymore […] consequently, I have waited for you.*

We observed that users lost trust in the monitoring of their energy usage in situations when they were confronted with information that did not match the actual and desired situation. Such perceived inconsistencies affected the general attitude of people towards the entire system. This aspect underlines the importance of direct and easy access and of usable systems.

> ***P19****: Well, we now we watched on the 15th […] there, I watched soccer on TV in the evening, I remember that. It would be interesting to see how much energy that requires.*

> ***Interviewer****: Well, than we have to check the 15th. […] you can now select 8 pm on the 15th in the selection menu of HEMS.*

> ***P19****: Indeed, it would be interesting to do that […] I am able to understand that exactly [...] that was just the TV and the computer I used to watch soccer. The TV has 400 W, we know that, and the PC 200. [Seeing the information on the screen] Strange, is that really possible? 4.2 KWh in the whole period from 8am to 11am. Definitely, that should be less […] well … if this is all correct? Maybe, you only get to see a tendency. [laughing] Now I understand why I was so surprised about my consumption elsewhere. Now, nothing surprises me anymore …*

In this case, the provided information displayed was correct, but a setting that grouped the information in the desired way was not properly configured. Our study shows that the trust in the system is especially important for the introduction of the HEMS, given that this is a new class of device and that electricity consumption is not well understood by users.

4.9. Doing it/impact on domestic ecology

The HEMS impacted the domestic ecology of the participating households. Participants identify appliances that are wasting energy and use them less or make plans to replace them. They also exchange less efficient behaviours for new and sustainable routines in their daily lives, which results in an overall reduction of energy consumption.

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

> ***P20****: Yes, well, we did consciously leave the light turned off here in the hallway. Usually we 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 the HEMS impacted the way participants use electricity and, as in the case above, identify and change a wasteful practice. Also, as in the following example, they considered an alternative practice that does not require electricity:

> ***P21****: 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.*

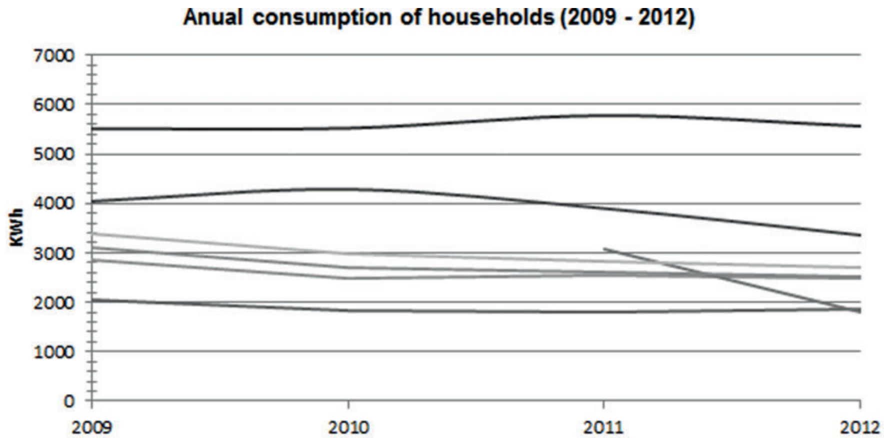
Another common observation was that once householders had established an understanding of their local energy system through the HEMS, they conducted energy conservation activities that optimized the rearrangement of appliances. The following case taken from an evaluation workshop illustrates this effect:

> ***P22****: Especially upstairs in the area, as I said before, I don't leave the TV on standby [. . .] I really turn it off.*

We also observed that participants used multi-socket outlets to merge devices and to be able to turn them off together. Participants also changed their configuration to achieve the previously identified saving potentials. Here, it was not just appliances, which are immediately accessible for domestic use, that came into focus. We observed that people also took into account constituent elements of the household, like heating (Fig. 11):

> ***P23****: I've separated the heater downstairs, because the circulation pump is always working and it consumes about 70 W, so I installed a timer. Only if the timer is on, he pump will also turn itself on.*

Beyond the change of routines or the changes in using existing devices, the 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.



	2009	2010	2011	2012
H1	-		765,5 kWh *	1804 kWh ↘
H2	3106,29 kWh	2691 kWh ↘ -13,37% -415,42 kWh	2614 kWh ↘ -2,84% -76,40 kWh	2515 kWh ↘ -3,80% -99,23 kWh
H3	3370,20 kWh	2990 kWh ↘ -11,27% -379,71 kWh	2840 kWh ↘ -5,04% -150,77 kWh	2698 kWh ↘ -4,97% -141,24 kWh
H4	2856,76 kWh	2475 kWh ↘ -13,88% -382,16 kWh	2536 kWh ↗ 2,48% 61,33 kWh	2486 kWh ↘ -1,98% -50,21 kWh
H5	5512,10 kWh	5520 kWh ↗ 0,15% 8,02 kWh	5778 kWh ↗ 6,67% 257,71 kWh	5561 kWh ↘ -3,76% -217,30 kWh
H6	4042,61 kWh	4285 kWh ↗ 5,99% 242,13 kWh	3899 kWh ↘ -9,00% -385,58 kWh	3359 kWh ↘ -13,85% -540,08 kWh
H7	2062,67 kWh	1847 kWh ↘ -10,46% -215,81 kWh	1788 kWh ↘ -3,17% -58,46 kWh	1863 kWh ↗ 4,14% 74,10 kWh

FIGURE 11. Overview of annual consumption of householders (*household 1 residents moved to a new apartment, information could only be tracked partly).

P24*: 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 W, [means that] it must be good, but instead that you might say, this vacuum cleaner running at 700 or 800 W might actually be more effective, because technology also evolves.*

These new insights into domestic energy consumption provided by the HEMS extend over the period of the field trial and show up as a noticeable effect when comparing the pre- and post-HEMS phases.

Overall, for the seven households, we see an average electricity reduction of 7.8% during a period of 18 months when compared with the consumption in the year before the HEMS deployment. Here, as shown in Fig. 12, an analysis of household 1 was not possible, because participants moved to a new apartment, making the collection and evaluation of relevant data impossible.

For the other households, only one household showed a significant increase in consumption (H5). In this household, however, remodelling took place during the study, which increased the living space significantly. Also worth noting is that in another household (H3) a person temporally moved out, which, independently of the HEMS, is likely to have caused a reduction in energy consumption.

While our sample size here is too small to generalize the impact of our HEMS and identify the exact impact of other factors in detail, it is worth noting that our results are consistent with the findings of other studies (Darby, 2006, 2001).

5. DISCUSSION

Our work, we suggest, partly confirms what is hypothesized in other research on energy monitoring in the home, but also extends it. In the following, we review each of our stated themes

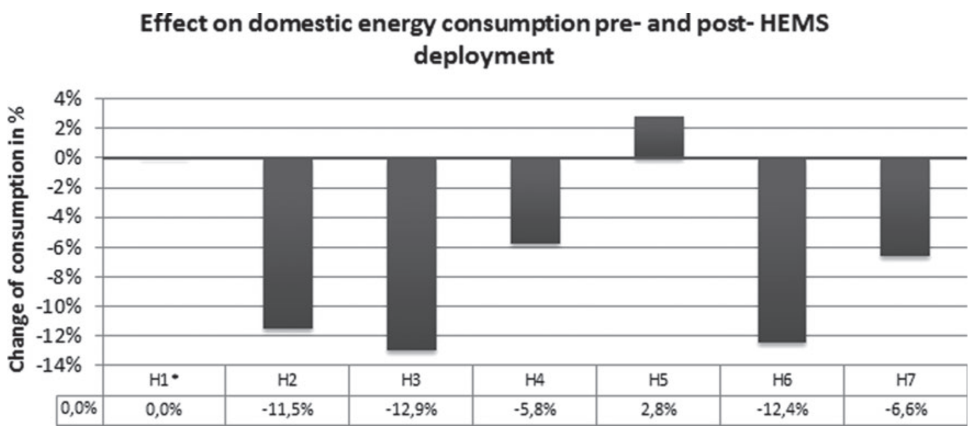


FIGURE 12. Effect on domestic energy consumption (*household 1 residents moved to a new apartment making a comparison impossible.

and their relation to previous work. We also discuss aspects for the design of future HEMS.

5.1. We are curious

Aspects of our first theme 'We are curious' have been highlighted in some previous research. People's curiosity for monitoring their consumption and beneficial effects of immediate feedback is partly described in (Darby, 2001; Fischer, 2008). Karjalainen (2011) also showed that people are interested in consumption information on an appliance level when tracking their use of energy.

Motivational aspects in relation to energy feedback devices are described in the recent literature, e.g. work by He *et al.* (2010), who argued that feedback devices should be designed for the specific stage of behavioural change a person is in, rather than a 'one-size-fits-all' approach. At different stages of appropriation, different things motivate people.

This theme, we feel, underlines that people are stimulated by the newness of the monitoring process but nevertheless that their curiosity dovetails with existing concerns about their energy use, and that real-time information is the preferred type of information. Our work nevertheless extends this sense of a curiosity in showing that the kind of interest participants displayed changes over time. In our study, participants altered their way of deploying sensing infrastructure in order to gain a deeper understanding of their energy consumption. For the design of future systems, the question of the correlation between motivational aspects to use the HEMS and pro-environmental attitudes is an important issue that arguably requires future research.

5.2. I or we

The existence of consumption feedback technology has an impact on household practices and domestic social life. The fact that different forms of use of such systems emerged around them has been previously mentioned in Schwartz *et al.* (2013a) and Van Dam *et al.* (2010). Hargreaves *et al.* (2010), for instance, pointed out that for their out-of-the-box energy monitor, men were the dominant users. They suggested that if usage of energy monitors changes to broader household 'communities of practice', this pattern might change and further longitudinal and ethnographic research is necessary to explore in greater depth how energy monitors are embedded into daily practice (Hargreaves *et al.*, 2010). Our research indicates that their intuitions are correct. Patterns of household interaction inform patterns of energy monitoring. Although it probably remains true that men are more likely to be the energy 'experts' in the household, we identified an emerging pattern of collaborative enquiry into domestic usage. It is difficult, on a very limited sample, to assess whether this is a function of the difference between democratic versus more patriarchal households but further research may illuminate the reasons for this. Certainly, in some form, acts of persuasion and conviction are commonplace. Either individually or collaboratively, monitoring forms part of the construction of the moral universe of the household.

For the design of future HEMS systems, we would argue, opportunities to support such forms of communication should be taken into account to bridge the gap from the mere presentation of consumption data to an actual behaviour change better.

5.3. Energy literacy

Compared with the previous themes, the theme of Energy Literacy is not particularly salient in Sustainable Interaction Design (SID) literature. Studies only discuss learning aspects following on from the provision of energy monitors as a marginal issue (Hargreaves *et al.*, 2010). This is likely to be because there have been relatively few longitudinal studies and so learning trajectories have been less visible.

We understand energy literacy as the development of a competence to deal with and make sense of energy in relation to a local, personal frame of reference. This competence is an important precondition for an informed reflection on the actions that may lead over time to significant reduction in energy consumption. Beyond personal consumption, energy literacy also, in principle, plays an important role in empowering people to become informed citizens who have the knowledge to part-take in the societal dialogue on shrinking energy resources. Here, the idea of energy literacy responds to the repeated calls from the sustainable research HCI community to allow users to take part and understand the values that are hidden in energy-saving technologies (Schwartz *et al.*, 2013a).

We therefore argue that the design of the HEMS should take people's existing level of energy literacy into account. The HEMS could provide different entry points, ranging from novice to expert users or, following the idea that literacy develops through the use of the system, change over time. Additionally, the system could support different modes of interaction depending on the literacy level.

5.4. Being proud

As with the previous theme, the presentability aspects of household monitoring are not well investigated in the field of SID. Although Hassenzahl (2006) investigated the attractiveness and perceived usefulness of interactive systems, and included the dimension of hedonic quality, with its attributes, 'presentable' and 'status', little or no research has yet been done into the extent to which such issues extend into networks beyond the household and what consequence that might have for our understanding of sustainability.

In our study, we observed that people accepted the system as part of their daily life, identified with the system in such a way that they could be said to be 'proud' and often used the system as a means of displaying their involvement with a worthwhile enterprise to their friends. Again, we remind readers that this is a small-scale study and the possible ways in which these network effects might be scalable remains to be seen. Even so, there is a potential for HEMS design to incorporate 'social' features of a kind that allows others to perceive possible benefits, or monitor energy consumption, outside of the immediate household (one thinks of the potential of such technologies in supporting the elderly). Normative relations in relation to energy use in wider family and community contexts are not well explored as yet but our research at least points to a possible direction for future work. Special modes for presentation and the ability to share personal energy consumption information appear especially relevant when considering the rapid growth of social media in recent years. Both local and remotsharing can contribute greatly to the overall user experience and value of the HEMS. At the same time, we know too little about the sources of enthusiasm, or pride, when energy consumption is in view. Future research needs to address the sources of motivation over time—we have no convincing picture yet as of whether these enthusiasms are the result of novelty, of specific features of the technology or of ideological commitments to the idea of being responsible, informed consumers.

5.5. Maintaining the overview

We know from SID literature that after an initial period of use, the usage of energy monitors tends to decline significantly over time (Hargreaves *et al.*, 2010). As a possible explanation for this, Van Dam *et al.* pointed out that the monitors themselves just became part of the 'background' within household routines (Van Dam *et al.*, 2010), which is in line with findings from Hargreaves *et al.*, who pointed out that their users had developed new patterns of energy use due to their increased awareness, and thus no longer needed to check the monitor (Hargreaves *et al.*, 2010). Other research identified issues related to the appearance, as well as aesthetic and design issues of such devices (Karjalainen, 2011) that may limit long-term user experience. Generally, long-term effects of energy feedback systems are not investigated enough (Froehlich *et al.*, 2010).

For our HEMS, and in contrast to some of the findings from above, we observed that people indeed make a sustained use of the provided HEMS system to maintain an overview of their energy use. While facing a limited decline in monitoring behaviour, system usage was sustainable over 18 months. As for the reasons, we can only speculate: In contrast to other work, for example, we followed an iterative and user-centred design process, thus adapting the HEMS to emerging and evolving needs and interests, and thereby adapting system design to the learning curve of the user. Here, further research will be needed to investigate factors that influence sustained HEMS use.

5.6. Individual accounting

According to Darby feedback needs to be clear, immediate and user-specific to be understandable (Darby, 2001). The theme *individual accounting* confirms these findings, but also points to a common problem: many people have problems with understanding abstract units and, for instance, do not understand the difference between watts and kWh (Karjalainen, 2011). In particular, our study shows how users, in their lives, make sense of individual consumption in specific ways and how such sense-making processes creates new meanings for abstract units.

To design energy monitors, it seems that units like kWh are the optimal solution as they measure the objective, physical reality of energy consumption most clearly. However, the phenomena of individual accounting reveals that energy consumption is first of all an entity of the life world that is connected with, but not reducible to, the psychological world [66–68]. A similar observation was made by Wilhite *et al.* (2000), who pointed out that people do not consume energy, but use services that consume energy (e.g. by using the Internet in an assembly of devices and appliances like PC, Monitor, Router, Data Centres' etc.). Providing clear feedback does not in and of itself mean materializing an invisible physical reality (Pierce and Paulos, 2010), and hence we must consider the social construction of energy consumption. Specifically, supporting individual sense-making practices is a rather different problem to that of simply providing feedback.

Our tagging and grouping mechanisms proved to be highly supportive as they allow users to build up their own vocabulary. Designers for the HEMS can create features that specifically support these individual accounting strategies and thereby allow users to customize the systems according to their personal evolving energy accounting practices.

5.7. Embedded in daily life

Far from being a neutral technology, our findings suggest that the HEMS should be embedded in social practices at home. We observe that the appropriation of the HEMS was particularly intensive in cases where the use of the HEMS fits into familiar and established routines of using technology and, most notably, when integrated into watching television. It seems therefore beneficial to integrate the HEMS and interaction with the system into existing practices, instead of asking users to do something entirely new. Hargreaves *et al.* pointed out the importance of putting the energy monitor where it would be seen regularly (Hargreaves *et al.*, 2013) and we take this further with suggestions concerning 'embeddedness'.

Our study suggests that such embedded design is a key issue for sustained use, as described before. Connecting the HEMS system to existing media devices and to established routines has caused people to use the HEMS for a long period. For our participants, watching TV was an established routine (and perhaps one of the few that involves family members being co-located) and using the HEMS became an activity incorporated into watching TV. HEMS system design thus, we believe, should consider integrating systems in the existing media infrastructure and media usage patterns at home. In addition, the design of the (routine) interaction with devices and the design of consumption feedback should be brought together to support long-term feedback usage. Hence, research on consumption feedback and research on the smart home should not be divided in two separate sub-communities, but should learn from each other.

5.8. Losing trust

In relation to the category *Losing Trust*, there has been very little systematic previous research in the field of SID. Research in other domains, however, has already addressed questions concerning the attitudes of users towards interactive technologies based on critical incidents when using them, or software failures overall (Feng and Lutz, 2008; Lippert and Davis, 2006).

In the case of the HEMS, when data were misinterpreted, this raised critical attitudes towards the entire system. This may be affected in the circumstance where there is no additional control or tracking opportunity besides the HEMS and people have no other means to track their consumption. While on the one hand that emphasizes the relevance of the HEMS as a unique resource within the home, on the other hand, malfunctions and failures have a disproportionate effect. This also underlines the challenge of delivering feedback on energy consumption in a robust way, as argued in other research. As known from previous literature, energy is perceived as being invisible by consumers and (technical) support is indispensable in facing the challenge of monitoring and controlling it. Problems using these tools could not only lead to failure of understanding, which would hinder the positive impact on energy consumption, but rather implies unanticipated and negative impacts in practice.

For the design of future HEMSs, avoiding possible misinterpretation of consumption data is likely to prove important for its potential negative influence on the sustained use of the HEMS. In addition, the systems should allow the user to trace the aggregated consumption data back to the raw data of the digital measuring in order to increase trust and traceability of the processed data.

5.9. Doing it

A key theme of studies in the field of human–computer interaction is the difficulty of changing household behaviour to reduce energy consumption. A large number of studies have investigated the effects on energy consumption by enabling energy consumers to better understand the usage of resources and to identify and realize energy saving potentials by providing interactive supportive technology (Darby, 2001; DiSalvo *et al.*, 2010; Fitzpatrick and Smith, 2009; Mankoff *et al.*, 2007).

In general, energy feedback systems are considered to influence consumers by providing feedback and increasing the awareness of energy consumption with the goal of realizing the potential for saving energy. Darby showed, for example, that feedback mechanisms can influence energy consumption in a positive way and can increase the potential of energy savings by 5–15% (Darby, 2006, 2001). Our study confirms these findings.

Our interviewees also reported using feedback from the monitors in order to plan new routines or change lifestyle practices, as a means of cutting back on domestic energy consumption, as already reported in (Hassenzahl, 2006).

Important for us is that saving energy, while an initial driver and overarching goal, cannot be achieved directly. Instead, other factors, as described in the other themes, constitute pre-conditions before energy can be saved in a sustainable manner.

6. CONCLUSIONS

In this paper, we have presented results from a longitudinal qualitative study of the HEMS that has been rolled out in a living lab setting in seven households for a duration of 18 months. In so doing, we have tried to shift the focus away from the more mechanistic, technology-led orientation of much of the literature towards a more consumer-focused, interpretive, approach. In so doing, we have demonstrated that consumption in this context should not be viewed simply as an individualistic and essentially rational decision-making process, but instead to see it as one that is produced in a social setting, by focusing on 'what people do with technology', which allowed us to uncover the appropriation of the HEMS from a different perspective. These methodological choices provide an obvious benefit insofar as they provide us with a 'rich' picture of user interactions over time and their professed rationales for their choices. As a result of our choices, we have identified some under-examined themes, notably in respect of the collaborative understanding of energy use that evolves over time, both within and beyond the household and the degree to which a learning curve defined some changing patterns of use and understanding. We should note as well, however, that such choices come with a cost. Our sample is small and it is not possible to generalize in any strong sense. Rather, we think of our research as illuminating some themes that have hitherto been relatively under-examined in this domain. Our goal was to provide a rich description of relevant and meaningful issues emerging from the use of the HEMS, in order to understand how feedback works in the wild. Based on our findings, we presented nine themes and discussed them in relation to existing research in the field of SID.

A great challenge for designing solutions for the mass market is that energy consumption is not to be viewed merely in terms of numerical totals, but rather as an entity in people's lives that can have many individual meanings. Despite this 'subjective' character, people are curious and expect to be informed in a neutral, reliable manner about their consumption. In this, the perception of the quality of the measuring system influences important values such as trust and identification, which can achieve a long-term impact and goes hand in hand with changes in consumption patterns.

To satisfy this need for objective information, we have argued that design should support the energy accounting practices by which people construct a reliable interpretation for their local context and their local needs. Supporting systems should render visible 'sense making' processes, by allowing users to trace back from the feedback into measured raw data. The appropriation of feedback systems creates in users a form of literacy that should be supported by the HEMS system. This means that design of the HEMS should take into account and adapt to the dynamic change in the skills and needs of its users. The HEMS should be designed to co-evolve with the changing competences of its users.

As we showed above, HEMS usage can be connected to the use of other existing media (like watching TV), which raises several opportunities to embed feedback on consumption in daily life. Our study uncovered some of these opportunities (Redström, 2008), such as the use of regular commercial interruptions as a slot where users switched to the energy monitor app running on the iTV. We observed a challenge in the need for smart metering technology to be always on in order to measure continuously, but at the same time to be as energy efficient as possible. An answer to this challenge lies precisely in integrating HEMS functionality into other existing home devices like Wi-Fi routers. These issues show clearly that consumption feedback design should be constructed through a holistic understanding of the home device ecology, since the ways in which HEMSs are integrated into daily life decisively impacts the attractiveness of the system and their sustainable use.

A final, but nevertheless very important, point has to do with the fundamental purpose of systems like HEMSs. There are, it almost goes without saying, a range of different political and ideological interests involved in the design of HEMSs. Against the backdrop of global environmental problems, there is an understandable demand by some principled parties to move to a more environment-friendly way of life. Of course, how much this move needs to or will take place raises a host of complex issues, ranging from the demands of individual freedom and control to the extent of social responsibility. We do not engage with these debates in any direct way other than to say that, as a matter of practical environmental politics in a pluralistic society, finding ways to persuade people to change their lifestyle is probably one of the few effective mechanisms we have. Participants in our study did not necessarily share a consistent view of environmental issues and we have no evidence that they were motivated by the same factors as researchers. Strengers (2008) has already pointed to the fact that there are aspects of consumption behaviour that are unlikely to change simply because researchers (or any other interest group) would like them to. These and other potentially conflicting objectives raise the questions of the ultimate goal of HEMS systems. Designers could primarily design from the standpoint of the users as proposed by user-centred design (Lieberman *et al.*, 2006) and participatory design (Friedman, 1996); or could centre on the change of 'wasteful' lifestyles, which is often implicitly the case in persuasive design approaches (Ehn, 1988). Here, the concept of value-sensitive design (Friedman, 1996) might prove helpful to deal with the diversity of interest by at least making them explicit subjects of an informed discourse.

With the growing needs for a change of direction in our energy consumption practices, interactive technology will increasingly play an important role in supporting people to manage their energy footprint. Our research has shown that there is a high potential for interactive technology, but assessing the impact of these technologies in daily life is non-trivial. In understanding this impact, further long-haul longitudinal studies will be of central importance.

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