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RESEARCH PAPER

Towards a User-Centered Feedback Design for Smart Meter Interfaces to Support Efficient Energy-Use Choices

A Design Science Approach

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Abstract Based on interviews of users' experience with current smart-meter technologies the authors propose, implement and evaluate a user-centered design of an energy-use information system that assists private households in making efficient energy consumption decisions. Instead of providing disaggregated data, the envisioned system automatically calculates the monetary savings from replacing an appliance or by changing the operational behavior of an appliance. The information provided is personalized with respect to appliance use and also comprises information from external databases. A prototype is implemented and evaluated in a use case with white goods household appliances. The study concludes with directions for further interactivity improvements and research into the structures of an openly shared appliance database.

Keywords Smart metering · Design science · User-centered design · Green IS

1 Introduction

The use of smart-meter technology greatly facilitates the collection and exchange of information about private households' energy consumption. In principle, this information could be used to make energy users aware of their household's electricity usage and, thereby, induce more sustainable energy consumption choices (Poortinga et al. 2003; Abrahamse et al. 2005; Mattle et al. 2011; Han et al. 2013). In contrast to the industrial sector, household energy usage continues to increase and comprises a large share of the total energy use. For example, in 2010 German households made up 27.7% of the domestic energy demand at 141 terawatt-hours (TWh) (AG Energiebilanzen 2014). For the EU, it is estimated that up to 27% of the housholds' energy use can be saved through more efficient energy use (European Commission 2006). According to the German Energy Agency, 50% of the electricity costs of German households are due to the energy usage of white goods, such as washing machines, dryers, refrigerators, freezers and dishwashers (Langgassner 2001). Furthermore, in the past years, both electricity use and the number of household appliances have increased almost constantly (Umweltbundesamt 2012). Thus, the household sector offers a large potential for improvements in energy efficiency that is to date largely untapped.

Field studies have confirmed that providing direct feedback information on energy use alone can potentially lead to savings of up to 15–20% (Abrahamse et al. 2005, 2007; Dietz et al. 2009; Grønhøj and Thøgersen 2011; Vassileva et al. 2013; Pullinger et al. 2014; Lossin et al. 2016; Zhou and Yang 2016). However, in practice unfamiliarity with the provided technical information (Abrahamse et al. 2005), information overload (Loock et al. 2013), and lack of means to interpret current electricity consumption make it difficult for the end user to turn the information into action (Fischer 2008; Simmhan et al. 2011; Darby 2010). For example, a consumer survey issued by the German Federal Ministry of the Environment regarding environmental awareness in Germany revealed

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that 20–30% of the representative sample ($n = 2034$) felt that a lack of transparency prevented even larger changes, e.g., making more sustainable energy use choices (Kuckart et al. 2006). Social economic factors, such as age, gender, education level and income, showed no impact on the survey results, however the participants all agreed that the consumer must save energy in everyday life. Moreover, recent field experiments supplying access to energy-use information through web-based or dedicated displays have shown that the realized energy savings are usually short lived as they disappear once the feedback information has been discontinued (Hargreaves et al. 2013; Pullinger et al. 2014; Van Dam et al. 2010, 2012), and that the feedback did ultimately not lead to an altered appliance usage (Thuvander et al. 2012; Hargreaves et al. 2013; Van Dam et al. 2010).

While generalized feedback has failed to evoke interest and make sense to energy users, McMakin et al. (2002, p. 860) found conclusive evidence that "an effective intervention must be customized to the population and situation being targeted." To this end tailoring (providing customized energy-use feedback) and modeling (providing examples for altered behavior) as well as goal-setting are recommended means of feedback intervention that have provided to improve upon generalized feedback in field studies (Abrahamse et al. 2005, 2007; Benders et al. 2006; Allcott and Mullainathan 2010; Vassileva et al. 2012; Loock et al. 2013). However, among others (e.g., Fischer 2008; Simmhan et al. 2011; Van Dam et al. 2012) Darby (2010, p. 455) concluded in her review on smart-meter interfaces and energy-use information that the provided feedback has yet to be further developed to provide more "appropriate forms of feedback, narrative and support". In particular, current smart-meter interfaces lack the ability to influence behavioral energy-use practices by determining "how much energy each practice uses and derive options for change" (Pullinger et al. 2014, p. 1150). This would require to measure "energy use per appliance and tailoring advice to the households' specific appliances" (Pullinger et al. 2014, p. 1150).

The *objective of this study* is to overcome this shortcoming of existing energy-use feedback systems and to design an artifact that is able to provide private households with tailored energy-use decision support on the impact of behavior change and appliance exchange. In particular, under the design science research paradigm we follow a user-centered approach to derive five requirements and eventually four distinct design principles for a future energy-use feedback system. More precisely, we propose to provide users with continuous energy-use data at the appliance level (Design Principle 1), which is then processed to automatically identify appliance states and settings (Design Principle 2). This allows to determine a personalized usage profile of the appliances in a household as well as the actual energy consumption of appliances, given the personal usage profile. The internal information gathered in this manner can then be compared to external information from appliances databases to provide decision support on behavioral changes as well as the replacement of an appliance (Design Principle 3). Finally, we suggest to provide decision support based on monetary savings or, for a long-term perspective, derivatives thereof, such as amortisation periods (Design Principle 4).

After having identified and motivated the problem as well as our design objective, the remainder of this article is structured as follows: Next, we discuss our methodological approach in the context of design science research. Then, based on this approach, we identify the solution objectives, i.e., the user-centered design requirements. Next, design principles are derived that incorporate these requirements. Subsequently, the feasibility of the energy feedback system based on these design principles is demonstrated in a prototypical implementation. Finally, the artifact is evaluated and discussed, including limitations and directions for future research.

2 Methodological Approach

To ensure a rigorous development of the design we adopt the design science research (DSR) methodology, which is deemed suitable to "create and evaluate IT artifacts intended to solve identified organizational problems" (Hevner et al. 2004, p.77). This methodology framework assists research of design theory that is prescriptive, practical, and a basis for action (Baskerville and Pries-Heje 2010). Additionally, the well-defined structure of design science also strengthens the potential for cumulative development of the artifact (Gregor and Jones 2007). In particular, we follow the process model developed by Peffers et al. (2007, p. 64) and pursue what the authors call a "design- and development-centered approach". That is, we build on a previous routine design instantiation of an energy-feedback artifact (a state-of-the-art smart metering device with web interface) that is evaluated through a field experiment and from which requirements and design principles for an improved artifact are derived. See Fig. 1 for an overview of the design science process pursued here. The entry point for this research is highlighted and the nominal design science process shows the sequential structure for both, the proposed DSR methodology and for this article.

After an evaluation of the challenges that the experimental participants have with adopting and using the current energy-use information design, Wallenborn et al.

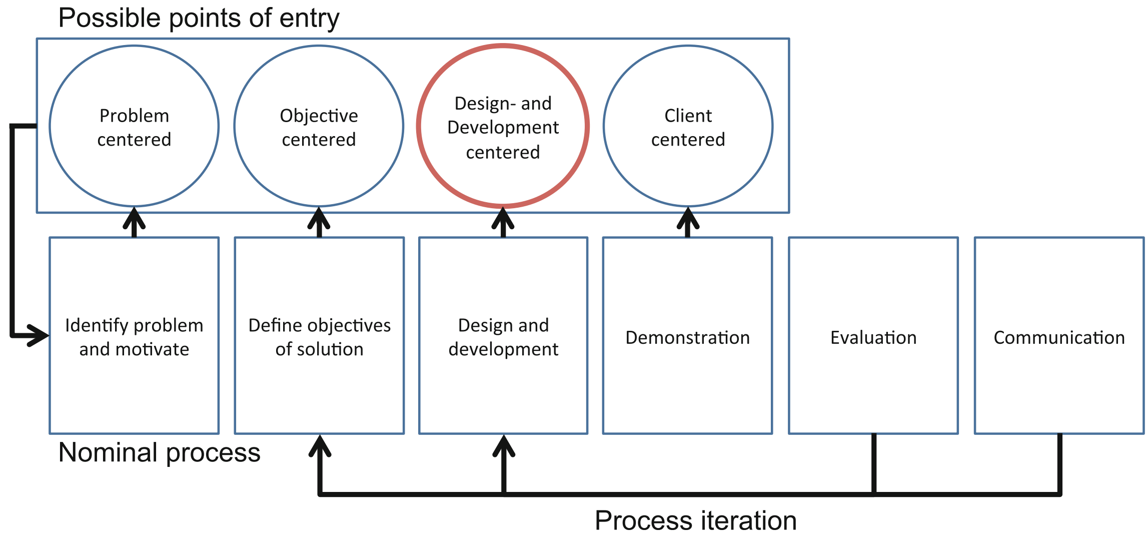

Fig. 1 Structure proposed for a design science methodology (Peffers et al. 2007), highlighting the design- and development centered approach entry point and the nominal process adhered to in this study

(2011) recommend researchers to integrate the users in the design process. Embracing a user-centered design has been suggested as critical for "the migration of electricity users to the demand response world" (Honebein et al. 2009, p. 39). Therefore, the requirements of the design artifact identified in this study are based on the user experience of a previous instantiation of the artifact. The six core principles of user-centered design are that: (1) the design is based upon an explicit understanding of users, tasks and environments, (2) users are involved throughout the process, (3) the design is driven and refined by user-centered evaluation, (4) the process is iterative, (5) the design addresses the whole user experience and (6) the design team includes multidisciplinary skills and perspectives (ISO 2010).

Design development is a continuous process and this study focuses on the first iterative step. We will not focus on developing the user-centered design theory; instead, we agree with Goes (2014, p. vi) that the contribution of DSR is not restricted to theory and that research rigour can be "pursued in the methods employed in the development of the artifact". Thus, by following Peffers et al. (2007)'s DSR methodology our contribution is the establishment of design principles for the stated objective as well as the development of a prototype. As we propose a new design to a known problem, our design artifact qualifies as an "improvement" in the terminology of Gregor and Hevner (2013). In particular, our design science research artifact differs from routine design as we propose and envision the use of non-standard solutions, which are technically feasible but, in combination, currently not readily available for routine design efforts.

3 Objectives of the Solution

Following Peffers et al. (2007), the objectives or (meta) requirements (Walls et al. 1992; Eekels and Roozenburg 1991) are derived for the proposed solution artifact. Following a user-centered approach, the design requirements are based on experiments and qualitative interviews of households' experiences with a routine design artifact, i.e., a state-of-the-art smart metering device with a web interface that provides immediate and historic feedback on the household's energy consumption. In particular, the main source of user input is based on our own semi-structured interview with 21 participants who took part in a three-month field experiment with this type of frequent energy-use information.

The interview questions covered the topics of energy awareness, flexible energy usage and privacy. The questions were asked open-ended and in an order that came natural during the interview to allow the users to freely explain their experience with the information provided. The recorded interviews were coded by labeling specific phenomena in accordance with grounded theory (Corbin and Strauss 2008). To build theory around the utility of energy-use information the phenomena were analyzed for common themes (Urquhart et al. 2009). By writing and sorting memos of these diverse subjects seven categories were established, which defined the participants' processes in regard to the energy-use information. These seven categories were (i) general energy use practices, (ii) energy use awareness, (iii) perceived energy use savings, (iv) practices with energy use information, (v) display limitations, (vi) ability to shift energy use in time and (vii) privacy concerns.

What remains from the grounded theory process is to analyze the interview results in light of related literature and experiments to find commonalities and differences that can extend the knowledge base (Corbin and Strauss 2008). In this study this amounts to studying related experimental experiences with frequent energy-use information and comparing our qualitative findings to them.

The first insight derived from the interviews was that users wish to learn or confirm the levels of energy usage of different appliances. For example, one user in our experiment explained his evaluation process where he turned off the electricity supply to all rooms except one from the fusebox and then tested the appliances of interest in this temporary laboratory. Furthermore, three of the 21 interviewed participants reported that the power use information had been used to support decisions to exchange appliances. Similar accounts of active user analysis of individual appliances were reported by Hargreaves et al. (2013) who interviewed 11 participants from the UK who got access to energy-use information over 18 months through dedicated displays. Vassileva et al. (2012) and Schwartz et al. (2013) also highlight the need for providing information at the appliance level to improve energy awareness and knowledge based on experiences from field and living-lab studies. Based on this evidence, we propose:

Requirement 1: The energy-use feedback system for private households should provide information about the energy usage of individual appliances.

The design artifact used in the field experiment provided energy-use data at a high frequency (every 8 s). It was found that this enabled a range of different information uses, such as determining the household base load, the influence of standby power and remotely monitoring roommates. Previous experiments also confirm that continuous provisioning of energy-use information is desirable (Abrahamse et al. 2005; Ehrhardt-Martinez et al. 2010; Hopf et al. 2016; Nilsson et al. 2014; Zhou and Yang 2016) and have led to a heightened awareness and knowledge level among household users (Darby et al. 2011; Hargreaves et al. 2013; Thuvander et al. 2012). Thus, we propose:

Requirement 2: Immediate, high frequency energy-use data is a fundamental requirement for an energy-use feedback system for private households as it improves awareness and allows for individual explorations as well as more advanced processing of the energy-use data.

Furthermore, the participants in our study were also interested in the impact of changes in operating behavior of individual appliances. Nine participants reported that they had tried to use certain appliances less often, for example, by only running the washing machine when full or by cooking food collectively. Although the operating behaviors were often evaluated, many commented that the impacts of certain changes were difficult to estimate when only aggregate energy-use data is provided. Hargreaves et al. (2013) similarly found that users would only go so far in changing their energy-use patterns since the impact was considered to be negligible or outside the preferred comfort zone. However, activity level energy-use information has been found to improve the understanding of personal energy usage (Costanza et al. 2012). Correspondingly, many participants were surprised to learn the significant power use of some of the stand-by enabled appliances, which influenced them to disconnect these appliances from the electricity source when not in use. Disconnecting and gathering appliances on power outlet strips were also found in the living-lab study by Schwartz et al. (2013). Hargreaves et al. (2013) had a slightly different experience, as their users reported that the base energy use was quickly understood as the norm, and it is not reported whether it prompted any changes in appliance operation.

Behavior change has statistically been more important for improving efficiency than what the rising cost of energy could accomplish in the same time (Frieden and Baker 1983). Supporting the evaluation of the value of energy usage behavior is therefore important (Grønhøj and Thøgersen 2011; Pullinger et al. 2014). It has also been shown that changing behaviors to improve efficiency is more successful for saving energy, both in the short and long term, and is easier to implement on a large scale than curtailing behaviors (Ritchie and McDougall 1985; Benders et al. 2006). In summary, we identify participants' desire for an energy-use feedback system that facilitates the analysis of how different appliance operating-modes impact the energy usage. Thus, we propose:

Requirement 3: An energy-use feedback system for private households should provide information on the energy usage of different operating behaviors of individual appliances.

In our field experiment the feedback format was limited to current power load, measured in kW. In the interviews it became apparent that the participants mainly evaluated and discussed their energy usage in monetary units. One user directly criticized the current choice of interface unit as too technical. Another user went further and reported that the costs reported on the energy bill had a greater motivating effect to save energy than the current experimental feedback. This argument is strengthened by Kamb et al. (1998), who found that a monetary incentive outperformed other units of equal value. In contrast, altruistic feedback, directed at the goodwill of users, show little or no effect on direct behavior change (McMakin et al. 2002; Ritchie and McDougall 1985). The importance of comprehensible feedback is also echoed by other experiments, where a more personal language is recommended to design future energy-use information systems (Thuvander et al. 2012; Schwartz et al. 2013). Thus, in an effort to present energy-use information in a motivating and understandable way, we propose:

Requirement 4: An energy-use feedback system for private households should provide feedback information based on non-technical units that are easily comprehensible to private household users, such as monetary units.

However, just providing energy-use information through comprehensible units may not be sufficient. For example, monetary units were criticized for being "unimpressive" (Wallenborn et al. 2011, p. 151), because the small short-term gains that were displayed with the live feedback did not motivate the users to change their energy usage (Wallenborn et al. 2011; Grønhøj and Thøgersen 2011). A related informational issue, which was voiced in our interviews, was the uncertainty of the impact of exchanging an appliance or operating behavior for another. For example, users expressed uncertainty on whether LED lights would be profitable over the current compact fluorescent or in how many years a more efficient washing machine would pay back the investment over the old one. This type of relevant decision support information cannot be satisfactorily answered with unprocessed energy-use data, irrespective of the unit used. Similar accounts were also evident in the study by Hargreaves et al. (2013), where the energy-use information also failed to provide a convincing argument of an action's value over a longer term. Generally, households seem to prefer technical energy-savings measures over behavioral measures (Poortinga et al. 2003), but especially the combination of feedback on behavioral *and* appliance alternatives is considered to be promising and has largely been untapped in previous design instantiations (Grønhøj and Thøgersen 2011). Thus, we propose:

Requirement 5: An energy-use feedback system for private households should provide users with decision support with respect to exchanging individual appliances as well as with respect to changing the operating behavior of individual appliances.

Finally, and for completeness, we note that our interviews also identified some contradictory requirements with respect to display technology and visualization of energy-use feedback, which precluded listing them as additional requirements. For example, participants were in disagreement whether they would prefer a dedicated display. Some argued that this would better remind them of the current energy usage, while others saw a potential risk of conflict if this information was always visible. Both the potential reminder and the risk of conflict from using a dedicated display was also voiced by the participants in Wallenborn et al. (2011) and Hargreaves et al. (2013) studies, who used different dedicated display technologies. On the one hand the information was backgrounded but continued to remind users of their actions passively, however on the other hand, this reminder was, in some cases, experienced as "nagging". Similarly, participants had contrary views with respect to the use of social comparisons and competitions in energy-use feedback. Although in some studies social comparisons are found to engage users and help motivate energy savings (Petersen et al. 2007), others only report negligible results (Abrahamse et al. 2005).

4 Design and Development

4.1 Suitability of Existing Energy Feedback Solutions

Routine solutions to provide private households with energy-use feedback information range from media campaigns over labeling schemes to home audits and smart metering devices (see, Abrahamse et al. 2005, for a comparative review). However, it is evident that the aforementioned requirements can only be fulfilled by a technical instantiation of an information system, and thus we will focus on a presentation of feedback provided by currently available instantiations of smart metering devices. A comprehensive list of commercial and non-commercial designs are reviewed by Weiss (2010) and Pullinger et al. (2014). Most devices are generally able to provide feedback not only on the amount of kWh used, but also in terms of costs, which is in line with Requirement 4. Furthermore, Weiss (2010) distinguishes broadly between those devices that report the households' total energy consumption and those that report the energy consumption of individual appliances be means of outlet sensors, which can also be combined to a mesh network that allows to monitor several appliances at once. In both categories, there exist devices that report energy use data at high frequency and are thus compatible with Requirement 2, but obviously only the devices in the latter category would be compatible with Requirement 1. The device proposed by Weiss (2010) is even able to detect on-off-states of individual appliances and thus provides functionality in the spirit of Requirement 3.

However, none of the devices reviewed by Weiss (2010), including his own design effort, offers contextual feedback on behavior change or appliance alternatives, which is demanded by Requirement 5. Similarly, Pullinger et al. (2014) identifies only one device in the UK market that is able to disaggregate total electricity use (fulfilling Requirement 1, 2, 4, and arguably 3), but highlights that "the provision of practice-based advice tailored to the household" (Pullinger et al. 2014, p.1151 and Table 1) is entirely absent, thus violating Requirement 5. This leads the authors to conclude that future versions of smart meters should include "specific disaggregation algorithms, types

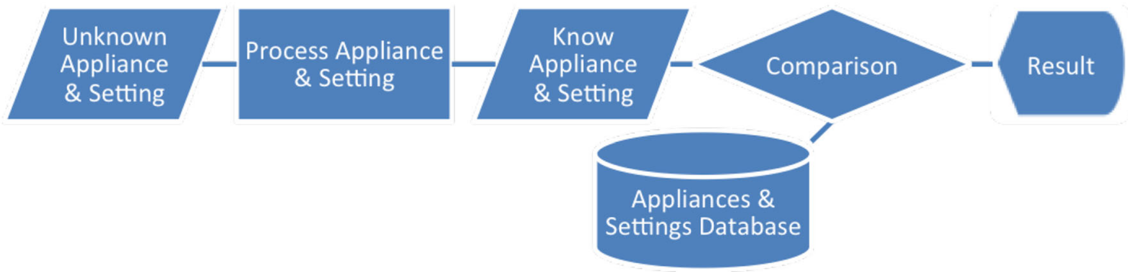

Fig. 2 Schematic design of the proposed energy-use feedback system

of feedback and criteria for tailoring their delivery to households based on their specific [energy use] practices" (Pullinger et al. 2014, p.1159). This is very much in line with the requirements and design that we propose here.

4.2 Design Principles

Hevner et al. (2004) proposed that designing a solution can be thought of as a search process. First the search will identify existing systems and related prototypes similar to what has been presented in the preceding sections. The aim of this search process is a set of design principles that will guide the development and ensure that all of the identified requirements can be met. Our design is based on several sources of data, which, through processing, are combined to advise private households about the current appliance and operation behavior options. Figure 2 shows an overview of the planned energy-use feedback system's modules and information flows, which we will now present in detail.

4.2.1 Load Monitoring and State Differentiation

The necessary appliance-level information can either be measured at the supply of the energy flow network by distributed sensors (distributed sensing) or by disaggregating load data at a junction point (central sensing). When the central measurement technique is successful, this approach could save the need for sensitizing single objects, however, it must be noted that such central disaggregation techniques are currently not reliably generalizable beyond laboratory environments (Liang et al. 2010). Since Requirement 3 specifically calls for behavior level information, reliable measurements and categorizations of individual appliances and their settings are necessary. This level of detail makes us opt for outlet sensing in this iteration.

Design Principle 1: Collect continuous energy-use data at the appliance level through electrical outlet sensors.

Furthermore, an automatic post-processing of the operational behavior data is proposed in this study. In this vein, only an initial manual setup is necessary, after which different settings will automatically be recognized for this particular appliance. The operation mode disaggregation algorithm that was devised to produce this data is based on a simple form of the Kirchhoffs law state model that was envisioned by Hart (1992). The basic premise is that every appliance returns to the original state through a program of a finite number of states. This model allowed us to analyze when a program finished (i.e., the appliances power consumption went back to the starting point) and to compare the duration of specific states of different programs to distinguish between them. To demonstrate this post-processing we focused on the identification of on and off states of the appliances. Specific signature sections of the different appliance programs were then extracted and labeled manually. However, this part could also be automated in future instantiations be means of machine learning (e.g., Zufferey et al. 2012; Hopf et al. 2016; Zhou and Yang 2016). The subsequent matching process followed automatically by comparing the duration of the signature sections. The process of disaggregating states and appliance settings are more fully explained in the demonstration (Sect. 5).

Design Principle 2: Provide information on appliances states (e.g., on or off) and settings (e.g., wash program) through automatic post-processing of the disaggregated energy use data.

4.2.2 Integration of Public Appliance Databases

An external source of data that provides information that is both useful for users and specific to each appliance are publicly available appliance databases (e.g., http://www.ecotopten.de). These databases, which contain energy-use data for a wide range of appliances, are well suited to perform general comparisons within and between appliances types. For example, the appliance data supplied from these sources could be used in a purchase situation to compare some legacy devices and new appliances available on the market. As users change their appliances or behavior this can be reflected in the feedback.

Unfortunately, to date these databases lack the depth necessary for the state and program matching that were explained above. Wiki-type projects for gathering and sharing information and appliance data like the PowerPedia (Weiss et al. 2012) are promising approaches in this regard and might eventually be the only feasible way of creating a global database of appliances and their operating modes. By introducing such a database, general appliance learning is reduced to the instance when the appliance is first measured. In order to demonstrate the value of appliance and behavior change, a prototype database with appliances that included the necessary appliance state and operational mode signatures information was designed in this study.

Design Principle 3: The appliance exchange and behavior change information is based on comparisons between internal information (appliance-level measurements) and external information (appliance databases).

4.2.3 Using Comprehensible Units

In order to provide a causal relationship between actions and their effects on energy efficiency, we propose to give decision support in the form of monetary savings. There are several advantages to this approach. First, in line with Requirement 4, money is a comprehensible unit and therefore has been reported to be accepted and well understood by a wide range of users (Fitzpatrick and Smith 2009). Monetary feedback can also be presented as investments over the long-term. This alleviates the concern of only negligible savings in the moment (Wallenborn et al. 2011). Moreover, it does not require technical knowledge and thus, it will also help to reduce the cognitive burden on the decision maker. Second, by using money as the feedback unit it is possible to compare different types of appliances between each other. This comparison is, e.g., not possible with the current form of energy labels as they are tied to a type of appliance. As the overall energy saving is the main aim of exchanging a certain appliance, being able to compare different appliance types would allow private households to exchange the appliance with the highest potential effect, irrespective of the appliance type.

Design Principle 4: Provide energy-use information support in the form of monetary savings, both in the short term due to behavior changes and in the long term due to appliance exchange.

5 Demonstration

In this section, we describe a proof-of-concept artifact that exemplifies how the design principles can be executed. It presents the outcome of the first iterative step in creating an improved, user-centered energy-use feedback system. To this end, we focus on well known household appliances to exemplify the data gathering, processing and potential presentation approaches.

5.1 Setup

In order to allow for detailed appliance level information, in line with Design Principle 1, a power outlet energy-logging device was used to gather data. The current and voltage is calculated continuously at the relative high frequency of 1 Hz by the microcontroller into real power. In accordance with Design Principle 2 the information post-processing of operating modes, comparison and visualization was then handled by a custom-made Java program.

Altogether, a washing machine, a dryer and two refrigerators were equipped with the energy-logging device. These appliances were chosen based on their common occurrence and relative large energy usage in households. To demonstrate the use of external information of alternative appliances, as predicated by Design Principle 3, related appliance energy-use data for the comparison database was gathered from the publicly available appliance benchmark information portal EcoTopTen (http://www.ecotopten.de). This website provides information on the most efficient household appliances currently available in the German market, and provides a relevant comparison for the analyzed appliances in this study.

5.2 Processing of Appliance and Operating Mode Information

To provide the necessary data for calculating monetary savings and amortisation (Design Principle 4), the logged energy-use data was processed for three parameters: (i) the number of completed cycles N^{cycle}, (ii) type of operating mode X and (iii) the appliance's energy consumption per cycle $E^{appliance}$. By combining the number of cycles and type of operating modes (e.g., 60 and 40 °C for a washing machine) with the energy-use measurements, the energy usage of a certain operating behavior, $E^{behavior}$, was determined. More specifically, the cycle counter identifies the return to the initial off state after a minimum predetermined length of time as a finished program cycle. In the case of the washing machine, a five Watt power use change from the initial steady-state was used as the threshold to register the start and stop of the appliance. The cycle start and stop naturally also framed the total amount of energy used (Fig. 3).

In the operating behavior analysis, the washing machine program load signature was determined to be the initial heating period in the beginning of the program, which is

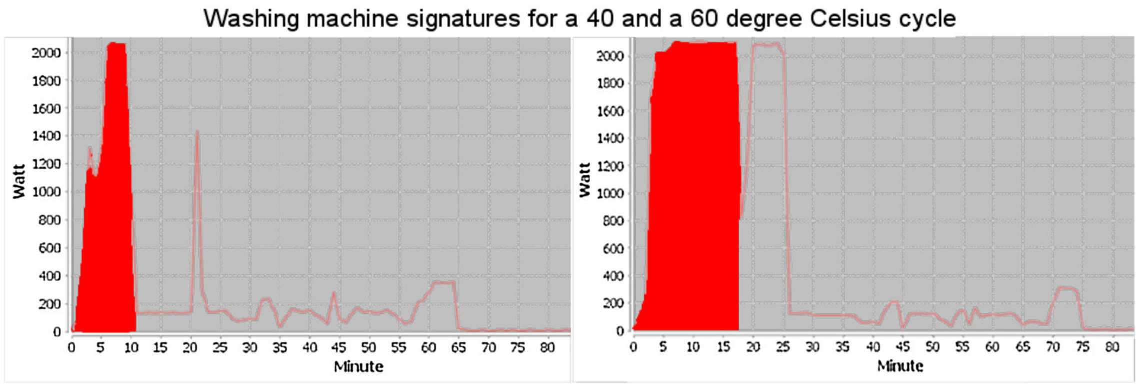

Fig. 3 Disaggregated states for a washing machine, showing the heating power surges used for determining the washing cycle used. The *area below the graph* represents the energy used during a certain time-span

the initial energy spike period marked in Fig. 3. This duration parameter could successfully sort all the 60 and 40 °C programs used in this study.

For the demonstration of feedback on behavioral changes we will focus on the monitored washing machine. There are two reasons for this choice. First, washing machines motors and heating blocks have a direct relation to the energy consumed. This is not necessarily true for all household appliances. Refrigerators, for example, are dependent on the temperature setting, ambient temperature, frequency and duration of door openings and closings and the thermal capacity of the content, which can only be read from the electricity usage indirectly. Measuring in- and out-side temperatures could alleviate this specific problem but is out of the scope of this design demonstration. Second, the operating modes of washing machines allow for a straightforward evaluation of behavioral changes. An example of a possible alternative operating behavior was collected by reviewing research on washing machine and detergent technology. A switch from 60 °C (140 F) to 40 °C (104 F) has, for example, shown to have little impact on the resulting cleanliness of clothes but will impact the energy used of about 125.58 kJ/kg water or about 230 Wh energy for 10 l of water (Rüdenauer et al. 2006).[1] This result provides a host of possible operational changes that do not necessarily have an impact on the quality of the service provided. Finally, washing machines are also often targeted by current energy efficiency support campaigns and provide a good basis for evaluating the defined requirements for this problem type in comparison to the existing energy feedback solutions.

5.3 Calculating Feedback

The parameters from the data processing were then combined to calculate the monetary savings associates with appliance exchange and behavior change (Design Principle 4). The known unit and amortisation requirements were catered to by processing the energy use from a unit of service (e.g., a full washing cycle) in monetary terms to appreciate the expected yearly gain.

5.3.1 Feedback on the Impact of Exchanging Appliances

With respect to the replacement of an appliance, the annual savings potential ($M_y^{appliance}$) can be calculated by the difference between the amount of energy for the current appliance (E_{cur}) and the alternative appliance (E_{alt}) in performing a specific unit of service (e.g., one cycle or one hour of time), multiplied by the number of the units of service per year (N_y) and the current price of electric energy (C_{kWh}), as shown in Eq. 1:

$$M_y^{appliance} = C_{kWh} \cdot (E_{cur}^{appliance} - E_{alt}^{appliance}) \cdot N_y. \quad (1)$$

Some appliances involve a greater investment and are predicted to be running for several years. The simple payback method is the most common indicator for evaluating the profitability of investments. Although it only provides a rough indication of the financial prospect, it is an estimate of how long the money will be tied up in an investment (White 1993). Equation 2 details that the yearly amortisation (A_y) is the quotient from dividing the purchase cost of the alternative ($C_{alt}^{appliance}$) by the annual savings potential of the alternative appliance ($M_{alt}^{appliance}$).

$$A_y = \frac{C_{alt}^{appliance}}{M_y^{appliance}} = \frac{C_{alt}^{appliance}}{C_{kWh} \cdot (E_{cur}^{appliance} - E_{alt}^{appliance}) \cdot N_y}. \quad (2)$$

[1] Specific heat capacity of water (4186 J/(kgdeg)) · temperature difference (60 deg − 40 deg = 20 deg) · water mass (10 l ≈ 10 kg) · Wh per joule (1/3600 (Wh)/J).

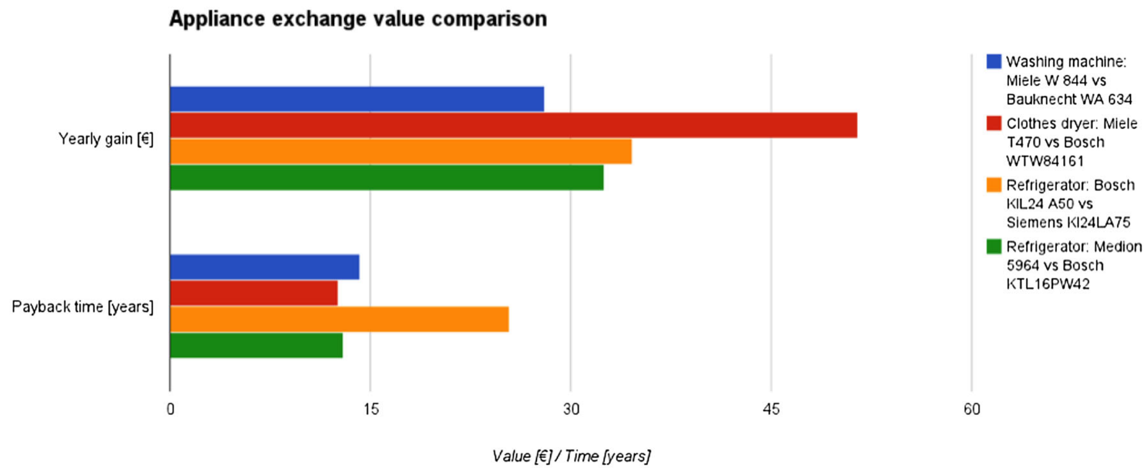

Fig. 4 Results showing the value of exchanging a washing machine a dryer and a refrigerator to a current top alternative of comparable size and program setting

This information further improves the basis for exchanging an appliance without demanding more sources of data to be collected. The problem formulation's simplicity also promotes a general understanding of the feedback given from the data.

Figure 4 demonstrates the feedback on the value of appliance exchange that was calculated based on data gathered by our prototypical implementation. The figure shows the different appliances tested and the monetary value in exchanging appliances for the current, most efficient ones listed in the EcoTopTen-database and the amortization rate according to the simple payback method. Energy prices (0.26 €/kWh) where taken from October 2012 from the German "Bundesverband der Energie- und Wasserwirtschaft" and the estimated purchase prices of the appliances from the online retailer Amazon. The operational life was assumed to be 12.2 years for the washing machine and dryer and 14.6 years for the refrigerator (Gutberlet 2008).

5.3.2 Feedback on the Impact of Behavioral Changes

The monetary value of changing operating behavior within the same appliance (i.e., the washing machine) was calculated for the current measured appliance and two newer alternatives. The number of cycles was normalized to be comparable to the yearly consumption base line of the analyzed appliances in the EcoTopTen database. The calculation to evaluate the behavior change in terms of monetary savings is shown in Eq. 3. The annual savings of behavior change ($M_y^{behavior}$) is calculated, similar to the savings from appliance change (Eq. 1), by multiplying the current electricity price (C_{kWh}) with the number of yearly cycles (N_y) and the change in electricity usage due to the behavior change ($E_{cur}^{behavior} - E_{alt}^{behavior}$). The factor X is a factor to vary the grade of operating behavior change between 0 and 100%. This variable was implemented to allow an evaluation of partial behavior changes.

$$M_y^{appliance} = C_{kWh} \cdot (E_{cur}^{behavior} - E_{alt}^{behavior}) \cdot N_y \cdot X \quad (3)$$

Figure 5 demonstrates the feedback that results from our prototype.

6 Evaluation and Discussion

6.1 Design Contribution

The objective of our design effort was to create a user-centered energy-use feedback system to promote effective energy-use choices in private households. This objective is pursued by involving users who have experience with energy-use feedback of a state-of-the-art routine design artifact. Based on qualitative interviews, design requirements were identified and operationalized through specific design principles following the DSR methodology.

Our main design contribution is that we have proposed and implemented an energy-use feedback information system for private households, which, in contrast to previous IS energy feedback solutions (cf. Sect. 4.1), provides tailored decision support on the impact of changes in behavioral practices or appliance exchange, i.e., which is based on the actual energy usage behavior and energy consumption of the individual appliances in a household. These new aspects of our design are codified in Design Principles 3 and 4. Such tailored modeling feedback is deemed valuable, because it is more clearly understood and may have the potential to yield sustainable changes in

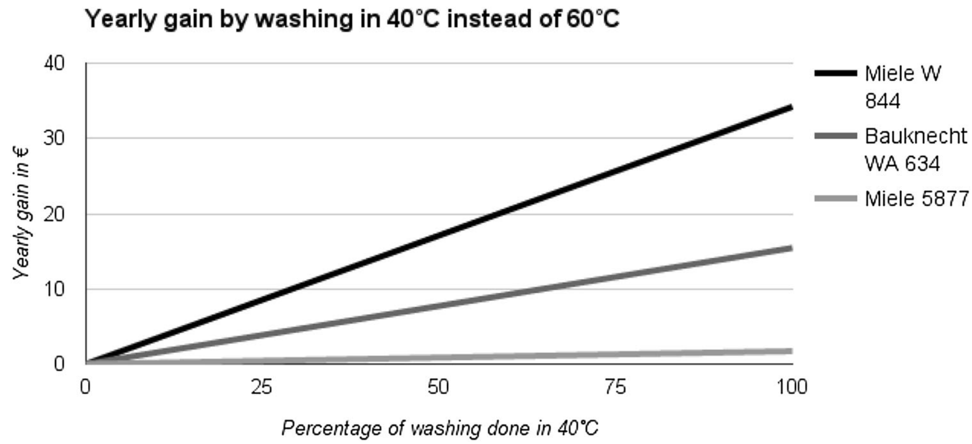

Fig. 5 Results showing the value of changing the washing machine operating behavior from 60 °C (140 F) to 40 °C (104 F)

energy-use practices towards more efficient behavior (Steg 2008; Grønhøj and Thøgersen 2011; Van Dam et al. 2012; Pullinger et al. 2014).

6.2 Limitations and Future Research

The devised design principles for smart-meter interfaces are defined and implemented in a prototypical artifact that lends itself well to continuous iterations. In particular, we wish to highlight three implications for future design improvements that can build on our design.

First, with respect to providing feedback on appliance exchange, this study has shown the potential that can arise from implementing a shared database for appliance energy-use data. Current publicly available databases support decisions between larger household appliances. However, it is still not possible to compare the current situation and most often not even the currently owned appliances with newer ones. For example, when comparing the expected operational life of common household appliances (Gutberlet 2008) to the calculated payback time, it is immediately apparent that replacing an appliance is, in many cases, not cost effective. Based on our demonstration, there is only a marginal chance of getting a return on investment when exchanging the Medion refrigerator or the Miele W 844 washing machine (see Fig. 4). With a shared appliance database with appliance setting differentiation, current appliances operated in specific ways can be used as the benchmark as was demonstrated in this study. The appliance efficiency could then be followed over its operational life, in contrast to the initial evaluation done today.

Although much of the necessary information can be gathered through several publicly available sources, such an appliance database is currently not available. It requires a community effort to accumulate the load profiles for various household appliances and their associated cycles and states. However, once this information has been added, it will benefit all other users with the same appliance. By uploading more usage parameters to the database, the accuracy of the expected mean consumption of the appliances can be improved which will extend the usability of the platform for the whole community. A potential avenue for research would thus be to investigate how the development of such a database can be established. This entails research on how appliance signatures can be standardized as well as how households can be incentivized to provide this information.

Second, our demonstration has revealed that, in the context of white goods appliances, a higher potential for savings is achievable by changing operating habits, as compared the savings associated with exchanging appliances net of replacement costs. This result confirms that being able to compare appliances based on the same (monetary) unit is key for making effective decisions both in terms of energy and economic aspects. Evidently, behavioral changes are generally more relevant for those appliances that are less energy efficient. Thus, the effect of changing the behavior is directly dependent on what appliance is currently in use.

Third, it is important to remember that, "feedback does not have to be complex to be effective" (Darby 2008, p. 506) . There is a clear risk that the ability to add more information to a system might finally make it more complex. Therefore, before implementing the proof-of-concept design for another quantitative and qualitative evaluation, the more fundamental concern of information overload should be evaluated. Due to the potential informational richness of an energy information system based on Green IS, research exploring how to balance the information for accurate and timely decisions is becoming more important. A strict separation and measurement of information design and interface design is necessary to build cumulative knowledge of how the adoptions process is influenced (Bhattacherjee and Sanford 2006). By combining the result from how an appropriate informational load should be designed with results from energy-use display design research (Anderson and White 2009), another set of interface requirements can be tested in the next design iteration.

Evidently, our study also bears several limitations. In order to focus on a clear presentation of the conceptualization and design of the envisioned energy-use information system, we deliberately chose a simple approach to conduct the underlying economic evaluation of different appliances and behavioral alternatives. Obviously, several improvements are feasible here. For example, the payback period could incorporate an appropriate discount factor, and possibly also a forecast on future energy costs. Moreover, it would also be feasible to provide monetary information on the outcomes that can be achieved by replacing appliances and changing the usage behavior. In this context, it might be worthwhile to extend the comparison engine in our system by a collaborative-filtering based recommender system that could disseminate best practices of similar households. It is important to note that the decision support provided only takes into consideration the electricity used, while other efficiency improvements - such as less water consumption for the washing machine - might also be an important reason to exchange appliances.

Finally, it is emphasized that the feedback system proposed in this study does not claim to be superior to all other forms of energy-use feedback. For example, the face-to-face interaction of home audits is arguably more personal than other forms of communication, and mass-media's ability to provide compelling and comprehensible explanations can be more powerful for introducing new services. However, the proposed system's ability to cover a broad range of key user-centered requirements that go beyond the current instances with the support of Green IS research is what could establish transformational power (Brocke et al. 2013). Naturally, the possibilities for innovation in Green IS go well beyond only using the information proposed in this study. For example, influencing attitudes of dissolution, i.e., that each individual has a very small perceived impact (Strengers 2011), could be targeted by integrating information about the power of many. Furthermore, normative beliefs could be targeted by providing comparisons between similar user and appliance groups.

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