Abstract

Integrating high shares of renewable resources into the electricity system requires a more flexible demand, especially more load-shifting in residential households. In order to achieve that different technologies, especially smart meters with various feedback functions, are tested on the market. So far little is known about the effects of a combination of different smart home technologies, such as smart appliances and an automated energy management system, that go beyond of providing households with feedback regarding their energy demand. Using an experimental design, test-residents lived in a smart home on KIT’s campus for several weeks. The results confirm the importance of real-time feedback systems for shifting loads, but indicate that other smart home technologies are helpful to maintain convenience in everyday life. For future design of smart home technologies it can be concluded that they have to satisfy information needs, provide cost-saving potential, secure high levels of flexibility and enable an easy use in everyday life.

1. Introduction

The aim of reducing GHG by 80% in Germany by 2050 (BMWi 2011) will cause major changes in the energy sector, because electricity will be increasingly generated from renewable resources. As these resources are partly volatile and hardly controllable (e.g. wind cannot be fully forecasted) it will be necessary to enable the electricity system to adapt to these new conditions. Different measures are under discussion that aim at matching supply and demand of electricity and include metering actual consumption more precisely (e.g. in real-time) and shifting loads so that consumption follows the current supply of electricity. In order to achieve this flexible demand there are some ideas how to incentivize residential households to shift loads to other times of a day when renewable electricity supply is available. This implies some adaptations to everyday behavior and routines, e.g. doing the washing at a different time of the day. However, promoting the sustainable use of electricity is particularly difficult, because it differs from other consumer goods: It is invisible, untouchable, and only consumed indirectly via related activities, such as working with a computer (Fischer 2007; Hargreaves et al. 2010). Providing households with feedback on their electricity demand, offering monetary incentives, and equipping them with smart home technologies might help to shift loads effectively in critical supply situations.

Some of these measures have been addressed in European and national policies. On a European level new conditions for private households have been enforced in the directive 2006 / 32 / EC which requires Member States to introduce, among others things, a meter that provides feedback to private households on energy consumption and energy efficiency. This directive has been transposed into national law in Germany (§ 40 Energy Act) and prescribes that energy suppliers have to offer some kind of electricity tariff that motivates residential consumers to conserve electricity and / or shift their demand from peak to off-peak periods. So far about 100 utilities in Germany comply with this law (Energate 2011). Furthermore new buildings have to feature smart meters since January 2010 if it is technically and economically feasible (§ 21g Energy Act). However, the number of households that are actually equipped with a smart meter is still very low in Germany. While smart meters are available to some extent, many utilities are still working on the development of accompanying products such as in-house displays that allow to monitor household’s electricity demand in a comfortable way. While a few smart household appliances are being offered on the market, their technical integration into some kind of household man-
agement system is currently under research and development as well. Full smart home solutions have thus not been offered on the market up to now (cf. also Fischer 2007). So hardly any consumer has experienced this future household environment on a daily basis, and therefore neither the consumer’s acceptance nor the effectiveness of these solutions (with regard to load-shifting and electricity conserving) is clear.

In order to find answers to these research questions we have analyzed the everyday behavior of test-residents in a fully furnished and operative smart home developed and built in 2010 by the Karlsruhe Institute of Technology (KIT). The smart home is part of the MeRegioMobil\(^1\) research project, which aims to find information and communication technology (ICT) based solutions to the challenges of an energy system with a higher share of renewable energies on the supply side and large consumers (in form of battery electric vehicles) on the demand side. Besides the development of the smart components and their techno-economic analysis, the user acceptance of these smart technologies is also evaluated within this project.

In this study four test-residents have been selected to move into the smart home on KIT’s campus for several weeks between December 2010 and April 2011. The demand-shifting potential of the ICT-based solutions was tested in three different phases: (1) First extensive feedback on the resident’s electricity consumption as well as on the power generation by the photovoltaic system (PV) was provided to the residents. (2) Then different electricity tariffs were tested for their motivational effect on shifting demand. (3) During the last phase an automated energy management system was introduced that enabled the smart appliances to react automatically to different electricity prices. The test-living phases were accompanied by in-depth interviews, a pre-post-questionnaire and an online blog.

The paper is organized in six sections as follows: first we summarize the state of research and outline our research questions. Then we describe the smart home setting and explain our research design. In section five we present the results of this experimental study. We close with a discussion of the results and recommendations for the future design of smart home technologies in residential homes.

2. Previous Research

As smart homes and the related products are not yet widely available on the market, there are only a few publications that include first-hand consumer experiences with fully equipped smart homes. However, there are some papers on the different technologies which constitute a full smart home environment, e. g. on smart metering, dynamic pricing, and especially the use of displays and other feedback options (Fischer 2007). Much of the research so far has been related to the consumer response regarding electricity conserving and cost savings, only a few consider specifically load-shifting. This section presents a brief review of the literature.

The main assumption behind most technologies introduced to field trials is based on an information deficit model (cf. Hargreaves et al., 2010): It is assumed that consumers lack awareness and knowledge of their electricity consumption due to its “invisibility” (Fischer 2007; Hargreaves et al. 2010). If consumers therefore had enough information, they could be able to change their demand. Feedback is therefore a popular element in field trials.

Darby (2010) summarizes research which proves that enhancing the frequency and comprehensibility of feedback on electricity consumption motivates at least some consumers to reduce their energy demand. Feedback can be given in two ways: Indirect feedback is mainly given through classical bills. Research has shown that the billing-frequency, detailed information (such as, an overview of consumption over time) and a good layout with graphs enhance the comprehensibility of the billing information (ifeu 2007). Direct feedback is usually given in real-time via more elaborated ways such as online platforms or in-house displays that are usually fed with data from the smart meters installed. The Energy Saving Trust (2009) explored in a focus group study what specifications of an energy display are desired by consumers. Displays should offer a clear indicator of current rate of consumption, a historic comparison of the consumption and the option of displaying units in power and money. Wood and Newborough (2006) suggest to also displaying environmental units such as CO\(_2\) emissions and Karjalainen (2011) stresses the importance of an appliance-specific breakdown of the consumption, i. e. information on what proportion is consumed by each appliance.

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\(^1\) Minimum Emissions Region and Mobility
The findings about consumer response, i.e. the decrease of energy demand, after introducing feedback systems are mixed: Darby (2010) indicates that in the reviewed studies energy conservation of between 5% and 25% are possible with higher reductions on direct feedback options (see also Ehrhardt-Martinez et al. 2010 for similar results). Other studies paint a less optimistic picture with regard to savings: Allen and Janda (2006) conducted a study which included real-time energy data feedback using a digital electricity monitor which was tried out by ten households over a period of several months. While there was increased awareness among the households, the actual effects on electricity consumption were marginal to non-existent (see also Pyrko 2011 for similar results). Even if electricity consumption is able to be reduced, the sustainability of this effect over time is a topic that is often discussed. In a study by van Dam et al. (2010) participants using home energy monitors were initially able to reduce their consumption by nearly eight percent, but were not able to maintain this reduction over a period of 15 months. Druckmann et al. (2011) show that in some instances there are rebound and backfire effects, that jeopardize and even increase the GHG emissions of households.

Offering a financial incentive seems to increase the effectiveness of feedback. Utilities have therefore introduced smart meters often in combination with dynamic pricing. Results from the GridWise Testbed Demonstration show that customer groups with a fixed rate reached about two percent savings, while the groups with dynamic pricing saved up to 30% on their electricity bill (Chassing & Kiesling 2008). These cost saving effects can either derive from electricity conservation (lower electricity demand as a whole) or from load-shifting (substituting lower-cost off-peak consumption for higher-cost peak consumption). A survey of demand response programs in the United States (EEE 2006) shows that mainly the second effect appears to exist: if peak reductions are achieved, they are often accompanied by an off-peak increase (valley filling) and conservation effects are therefore minor to non-existent. The German MeRegio field test with 1,000 households supports this result: while valley filling effects up to 17% were reported, the households reduced their overall electricity demand only by three percent (Hillemacher et al. 2011).

Not many quantitative results on the impact of using smart appliances in residential homes are reported so far. A field-test in California that introduced smart thermostats to residential customers reports a reduction of peak-consumption by 27% (twice as much as the control group) – two-thirds deriving from the smart technology itself and not from manual interventions (Charles River 2005). A recent study (Paetz et al. 2011) on consumer attitudes and perceptions reveals that residential consumers are not very open to behavioral changes in daily routines and require that demand response options should not be linked to reductions in comfort. Consumers therefore indicate high acceptance of smart appliances and home automation systems in general (see also Mert et al. 2009 for similar results).

To sum up, the current literature suggests that smart home technologies have the potential to support reductions of energy demand and peak-loads in residential households. However, researchers have found different effect ranges including zero reduction of energy demand. Results with regard to load shifting behavior point in a similar direction. Regarding consumer perceptions and acceptance, the studies published so far indicate that consumers usually show positive reactions when confronted with smart home related technologies. The main driver for the adoption of such technologies is the potential cost saving involved but consumers also anticipate several disadvantages (Hargreaves 2010; Paetz et al. 2011).

Literature findings do not allow hypotheses to be formulated neither about consumer acceptance nor about effects on electricity demand. So this study takes an experimental approach. The focus here is on consumers’ acceptance and response to the full range of a smart home environment experienced on a daily basis. How are the different smart home technologies used in daily life? Which elements are accepted most and how effective are they with regard to load-shifting? What are drivers and barriers for the adoption of these technologies?

3. **Smart Home**

In order to answer these research questions outlined above an experimental approach in a smart home laboratory was employed. While classical laboratory experiments allow portraying cause-and-effect relationships by controlling all parameters and reproducing results, field trials are conducted, if the research questions can better be answered within its natural context (Berekhoven et al. 2009). The smart home setting used in this study combines the advantages of both by providing an analysis under controlled conditions. On the one hand the smart
home setting allows a certain stability, because the technologies under research can be controlled, interventions are quickly possible (e.g. in the case of technical problems) and the experimental set-up can be reproduced. On the other hand the smart home resembles a field trial, because it is built up as a typical household, in which the test-residents can settle their everyday life. For analyzing the acceptance of smart home technologies, we therefore selected test-residents to move into the smart home and experience the technologies on a daily basis. This section describes the smart home and its components in detail before presenting the experimental set-up used in this study.

The smart home on the campus of KIT represents a building for two residents, which consists of a 60 sqm two-bedroom apartment and a 20 sqm equipment room (cf. Figure 1). The smart home includes decentralized suppliers, a (mobile) storage and electrical consumers. A photovoltaic system (PV) is installed on the roof and a micro combined heat and power plant (µCHP) is installed in the equipment room. A battery electric vehicles (BEV) is integrated over a charging station. The kitchen is equipped with several smart appliances: washing machine, dishwasher, tumble dryer, stove, and ceramic stove top. The smart appliances provide a range of features to the user; they are connected to a central communication gateway via power line. Thus, no additional hardware equipment is needed for the ICT-integration of the appliances. The gateway provides diverse data on the current status of each appliance, e.g. the program of the washing machine selected by the user or the remaining time of the dishwasher’s current program, and is able to receive simple control signals.

The smart home includes both, intelligent and non-intelligent appliances. Those connected to the communication gateway represent the intelligent appliances. In order to integrate the non-intelligent appliances into the Energy Management System (EMS, cf. Figure 2), additional relays and measurement equipment are installed in the smart home. A smart meter records the total energy consumption and is able to communicate aggregated data to the energy supplier for billing purposes quarter-hourly.

The term “smart home” is generally used for linking different separate devices of a household to a network. The term can therefore include aspects of ambient assisted living, entertainment, and security. In our research we focus on aspects of energy management, but aim to integrate the other aspects to this setting on the long-run.
Furthermore, an extensive measurement environment is integrated into the smart home for real-time monitoring of each electrical consumer and each power socket of the apartment individually. Electrical values like voltage and active power are periodically retrieved by the EMS and finally stored in a central database. This data can be used to analyze the user behavior with respect to electrical power consumption, but also for representing specific data to sensitize the users to the energy consumption of all appliances in the household.

An essential task of the EMS is to shift electrical demand from times of high demand and low supply to times of low demand and high supply (Becker et al. 2010). A dynamic electricity price signal is used as an incentive system assuming that it correlates to the situation in the electrical grid indicating an oversupply with a low price (and vice versa). The EMS is based on the observer/controller-architecture (Allerding et al. 2011). Its generic structure allows the integration of various components. Based on the electricity price information the EMS is able to re-schedule the smart appliances automatically within certain limits. The user has the possibility to define these limits by setting the time frame for running an appliance at the Energy Management Panels (EMPs).

![Fig. 3: EMP – Visualizing load information and price signals](image)

The EMP serves as connection between the EMS and the user. It displays relevant information, actions and features of the EMS and gives the user the opportunity to customize the energy management according to his/her needs. The EMP is provided to the smart home’s user by four touch-screen displays. Since it is a web application, it is also accessible via any types of smart and mobile devices having a touch screen (e.g. iPod touch).

The “Energy Consumption” tab of the EMP (cf. Figure 3) offers an overview of the current electricity demand in the household as well as information about the current electricity price and the amount of locally-generated electricity. The price signal shows the prices for the next 24 hours in advance in the diagram at the top of the window. Next to it there is a display of the current electricity price which changes its color according to the price signals (red: expensive, green: cheap). In the left column, the current total energy consumption of the smart home is displayed. Below, the currently supplied power of the decentralized power generators (PV and µCHP) is displayed. The difference between consumption and supply is the amount of power demanded from the grid. This value is negative when the sum of electric energy provided by the PV and the µCHP-unit is larger than the electricity consumed in the smart home.
If an appliance is ready to start, e.g. a dishwasher filled with dishes and detergent, the user may start the appliance at the desired time either manually or remotely in this window simply pressing a button. As describes above, the EMS can instead also schedule and start the smart appliances automatically at times of low electricity prices. The user can restrict the time frame in which the appliances may be running to match his/her preferences, e.g. to have the dishwasher finished in the evening on returning from work. The time frame is specified by entering a degree of freedom (cf. Figure 4). This is the time interval, within which the device needs to be finished. In the EMP the user can set the degree of freedom to her preferred time. The EMS will calculate the most cost-effective running time and communicate its starting time to the user. If it does not match the user’s timetable, he can still start or stop the appliance manually.

The menu option “Energy Supply and High Power Consumers” provides an overview of all the installed energy suppliers (i.e. PV system, µCHP), storages (i.e. BEV), as well as intensive power consumers like the cooling ceiling. The current state and the current power supply or consumption is visible beneath the icons of all the installed devices. When selecting one of the icons a detailed analysis of the devices’ state and behavior is shown in a special window. For example when selecting the PV system a diagram shows the power supply of the solar panels in the last 72 hours (cf. Figure 5). The PV system belongs to the local energy suppliers and cannot be controlled by the EMS. Therefore, the user can monitor the PV system but does not need any interaction.

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3 The µCHP, BEV as well as the cooling ceiling were not yet implemented when this study was conducted.
4. Research Design

Experimental Set-Up

Within the smart home setting described above, various experiments have been conducted during two test-living phases. The experimental set-up was structured into three modules (cf. Table 1) with the objective to analyze different effects isolated from each other keeping different variables within a module consistent. Furthermore we did not want to overstrain the residents with the innovative setting, but keep their interest high over the course of the test-living phases. The first module had been tested in both test living phases (T1 and T2), while modules two and three came into action during T2, as the duration of T1 (four weeks) was shorter than of T2 (eight weeks).

Table 1: Modular structure of experimental set-up in test-living phases T1 and T2

<table>
<thead>
<tr>
<th>Module</th>
<th>Test</th>
<th>Technologies in use</th>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feedback</td>
<td>EMP, i-App, billing (in T2)</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Dynamic Pricing</td>
<td>No additions</td>
<td>/</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>Automated EMS</td>
<td>Additional functions for smart appliances on EMP</td>
<td>/</td>
<td>✓</td>
</tr>
</tbody>
</table>

The objective in module one was to analyze feedback on electricity consumption in daily life. The feedback was provided in both test-living phases by the EMP and its application on an iPod touch (see section above). Thus the residents were able to check the load of the household and of each appliance, as well as the power provided by the PV in real-time. The electricity price was also displayed, but was kept static during the first module in order to meter a base load curve. In module two then several time-of-use tariff models had been introduced and tested for their practicality (cf. Table 2). All tariffs were calculated with an average price of 22 ct / kWh. Initially, a tariff with two price levels and a fixed time scheme (i. e. every day the price levels applied at the same time) was tested. The time scheme became more dynamic (i. e. the price levels applied to different times every day) when tariffs with more price levels were activated. Two tariffs with three price levels, but different price spreads were introduced in the following weeks, before testing a tariff with five price levels. During the last two weeks the tariff model with three price levels and a high spread was put on again in order to compare the manual with the automatic management of the appliances, as the automated EMS (and the full use of smart appliances) had been activated for these last weeks.

Table 2: Electricity tariffs tested in modules two and three during T2

<table>
<thead>
<tr>
<th>Weeks</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tariff structure</td>
<td>Standard Time-of-Use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Time scheme</td>
<td>Fixed scheme</td>
<td>Dynamic scheme</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price levels 1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Prices [ct/kWh] 22</td>
<td>12</td>
<td>17</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>14</td>
<td>7</td>
<td>7</td>
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<tr>
<td>28</td>
<td>22</td>
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<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
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<tr>
<td>Additions</td>
<td>Automated EMS</td>
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</table>

The test-residents did not pay any rent or expenses on electricity / water during their residence in the smart home. In order to offer them an incentive to deal with the electricity tariffs, a bonus-malus system was designed. For each kWh consumed in the lowest price zone, the test-residents received one bonus point and vice versa a malus point for each kWh consumed in the highest price zone. Each bonus point correlated to 0.5 euro. The value of their bonus balance was disbursed at the end of the test-living phase after completing the post-questionnaire. The test-residents were able to gain bonus points not only by shifting their electricity demand, but also by completing a few tasks, such as finding out the cost of watching the news on television. These tasks were
designed to further motivate the test-residents to get involved with their electricity demand in this smart home setting.

**Methodology**

In order to evaluate the experiments we analyzed the behavior and the perception of the test-residents with qualitative and quantitative data: By metering the electrical consumption in real-time, we were able to analyze behavioral data and evaluate it with interviewing material by conducting in-depth interviews, a pre-post-questionnaire and providing an online blog to the residents.

In-depth interviews are a method to elicit and explore opinions and are therefore especially useful if individuals are confronted with innovative solutions. It allows a close interaction with the researcher and the technology by giving the possibility for both interviewer and interviewee to ask questions and discuss them. Hence, the researcher has the chance to develop a deep understanding of why people feel the way they do by analyzing their verbal and non-verbal reactions (Bryman 2001). To complement the interviews (each with a duration of about an hour) short standardized questionnaires were handed out before and after (pre- and post-questionnaire) the test-living phases. The pre-questionnaire included items on attitudes towards technological innovation and the environment as well as electricity conserving behavior. The post-questionnaire included questions about general evaluations of the smart home and its technologies. During the test-living phases the residents were able to write about their experiences and give feedback in an online blog. The combination of these survey types enables to collect a rich amount of qualitative data in the participants’ own words. Figure 6 embeds the surveys in the general approach.

![Selection Process](image)

**Selection Process**

- **Moving In**
- **Test-living Phase**
- **Moving Out**

**Screening Questionnaire**

**Pre-questionnaire**

**In-depth Interview I**

**In-depth Interview II**

**Online Blog**

**Post-questionnaire**

Fig. 6: Surveys conducted within the study

The experimental research design does not allow gaining representative results, but enables the researcher to get deep insights of motives for consumer behavior. Thus the results depend strongly on the sample and selecting test-residents is an important step.

**Sample**

Two test-living phases with one female and one male test-resident in each phase were conducted between December 2010 and April 2011. While the first test-living phase T1 was carried out with two students, two “average adults” (=non-students) lived in the smart home during the second phase T2. The age of the test-residents varied between 22 and 31 years. Recruiting relatively young test-residents was motivated by the fact that they were regarded as one of the main target groups, as the technologies will probably be available on the market when they start settling down and investing in such equipment. Furthermore it was expected that the students would be relatively open-minded to the experiments, as they have not yet developed fixed habits for managing a household. For the second test-living phase non-students were therefore recruited who were more established with regard to household and profession.

Test-residents were recruited by an online advert on the webpages of the project MeRegioMobil and of the Institute for Industrial Production. Thus mainly persons interested in energy research signed up and were selected using a screening questionnaire (cf. Figure 6) that aimed at finding those that were generally interested in the topic, but had little pre-knowledge and no experience with the smart home technologies under research. Final selection took place after a house tour.

In the pre-questionnaire the test-residents were asked to indicate which two out of five topics were the most important challenges of our time. Environmental problems ranked first followed by unemployment and economic development. Health care and crime were rated as less important. Another question was how much they liked...
to try out technological innovations. While the non-students indicated “I prefer to wait until others have gained some experience with it”, the students ticked “I like to try them”. Thus the test-residents rated themselves as being environmentally aware and very to fairly open to innovations in general. The questionnaire also included some five-point-Likert-scaled items on energy conserving in everyday life. On these items, the test-residents described themselves as making some effort to conserve energy in daily life by trying to avoid stand-by consumption and using energy-saving lamps.

In the following section, the results of the test-living phases are presented and illustrated using test-residents’ statements of the interviews or the blog posts as well as their behavioral data. All the statements have been translated into English while retaining the gist of the original German. The digits after each quote refer to the first or second test-living phase (T1 / T2).

5. Results

In general, the test-residents showed high interest in detailed information on their electricity consumption and therefore intensively made use of the EMP and its functionalities. The EMP was the central point of interaction between residents and the EMS and was crucial when dynamic pricing was introduced to the experiment. The different electricity prices were a new issue to consider in daily life and the test-residents reported that they needed some “adaption” time until they fully understood the consequences of such variations in prices. Considering the response to dynamic pricing in T2 no conserving, but load-shifting efforts were observed. However we were not able to calculate absolute conserving nor load-shifting effects for three reasons: Firstly, due to some technical problems the base load curve of the first experimental week was not fully metered and could therefore not be used as a reference load. Secondly, the overall household consumption shows that the test-residents got accustomed to the smart home and its appliances after about three weeks (cf. Figure 7). Thirdly, the demand varied by up to 30 % from its average of 50.4 kWh per week, because business trips and family visits caused a lower resp. higher occupation (cf. Figure 7).

![Fig. 7: Household demand during the test-living phase T2](image)

Nevertheless, load-shifting was indicated by the electricity demanded during low-price periods and affirmed by the self-report of the test-residents. By comparing the average daily load curve (accumulated over the eight weeks of T2) with the German standard load curve H0, a similar structure was observed with a strong shift towards the evening hours (cf. Figure 8). By adding the price curve, a reverse effect between prices and demand was evident. By analyzing all three curves together, load shifting was visible in the evening / night hours (20:00 – 2:00) as well as over noon (11:00 – 14:00). However, these load shifting efforts were limited by the willingness to shift certain activities, such as cooking.
In our study the functionalities of the automated EMS didn’t increase the amount of electricity shifted during the test period of two weeks, but ensured more convenience in doing so. Thus the test-residents liked to activate the smart appliances for automating load-shifting after a certain familiarization time. They perceived numerous benefits for all the smart home technologies, the most important one being monetary savings followed by environmental protection. In line with this we found that the generation of electricity through the solar panels on the smart home had a motivational effect and loads were also shifted into sunny hours regardless of the current electricity price. For their own homes, the test-residents reported interest for the smart home technologies under the precondition that the investment in those was shortly paid back through monetary savings. Furthermore, high levels of flexibility should be ensured and the complexity of technical features maintained low.

In the following we show the evaluation of each module in detail using both test-living phases (T1 & T2) for the results on feedback (module 1) and the second test-living phase T2 for the results on dynamic pricing (module 2) and the automated EMS (module 3).

**Module 1: Feedback**

The first phase of the experimental set-up was planned for familiarization with the smart home setting and for a first habituation to the EMP. The test-residents were very keen on getting details about their electricity consumption and had fun on exploiting myths. They turned on various appliances, checked their consumption and cross-checked the appliances in use during a day.

“For half an hour I have turned on as many appliances as possible, even my hair curler. I was impressed by 7000 Watts and no shortage ;-), but shocked that the hoover needed 4000 Watts power. It’s like a game.” (T2 blog)

After a while the test-residents only consulted the EMP whenever a new appliance was in use, as they remembered how much power the frequently used appliances needed. Over time the interest in single appliances was outweighed by the interest in the total household consumption and its history.

“Now that I know all about the coffee machine and the TV, I’m more interested to know how much we have consumed over the last week or over the last month.” (T1 interview)

Even though no test-residents said, that the feedback itself changed their daily habits a lot, all of them agreed that it induced changes in their perception and their attitudes towards electrical demand. Two test-resident said that they even started to feel guilty when using the appliances (unless the PV system had supplied power at the same time). This in turn did induce smaller changes.

“This load curve has changed my attitudes. At least I know how much power the coffee machine needs. This morning for example I turned it off, because I knew my roommate was still asleep and I thought it doesn’t have to run for another hour without need.” (T1 interview)

The behavioral data do not indicate conserving effects either, still this was an important issue especially to the non-students. Consequently they were keen on more information about their electrical consumption. While the
EMP had provided information on the load of the household and of each appliance, the test-residents were missing a comparison on how much electricity they had conserved and / or shifted, and the direct impact on monetary savings. One resident was especially interested in knowing how his consumption was even in comparison to other households and suggested a regional competition that rewarded the winner with a bonus on his electricity bill.

These pieces of information had been given through a weekly bill in T2 (see Figure 9), but interestingly the weekly bills were not studied much. The in-home displays were the preferred feedback option, because the information was displayed in real-time and not ex-post. The iPod touch with the EMP-application was only used by the students. The non-students did not perceive an added-value of using the EMP-functionalities out of home, but were more concerned about transmitting the household data over the internet to a mobile device.

“I’m more conservative in this aspect. I prefer to keep the home data out of the internet. Simply for security reasons.” (T2 interview)

The test-residents frequently looked at information on supplied power by the PV system. Especially the non-students were interested and experienced this data intensively during the sunny months of their residence in the smart home. The non-students reported to preferably use the appliances during sunny hours; also later during the experiment when dynamic pricing had been introduced they stated that the supply of solar power was more motivational than the electricity price levels. As it was a sunny season and the self-consumption rate (34 %) was not much above the German average (30 %), a direct relationship between electricity demand and PV generation cannot be filtered from the metered data. In any case the transparency of the solar power supplied had increased the awareness for renewable resources. Both non-students reaffirmed several times during the test-living phase that they liked the idea of using locally generated electricity for several reason: first this was a monetary benefit, because no electricity had been demanded from the utility in sunny hours. Second it increased the independency from the utilities – this can be explained by certain distrust in utilities, also reported in other studies (cf. Paetz et al. 2011). Third it was a mental excuse when more electricity was demanded in sunny hours – this can be interpreted as a rebound effect, already mentioned before.

“Yesterday I was at home early in the afternoon and washed my clothes, used the tumble dryer and even hoovered the car. You’ll probably see that the consumption was high, but the solar panels produced a lot of electricity, so that’s ok then.” (T2 interview)

When thinking about the long-term use of an in-house display in their own homes, the test-residents suggested that further information was needed to provide more motives for checking the display regularly. The suggestions concerned comfort as well as security and not necessarily energy-related features, e. g. an integrated alarm clock in the displays located in the bedrooms or an integrated burglar alarm system. Some comfort features already integrated in the EMP’s were appreciated and used, such as the weather forecast or the light control.

“Every time before leaving the smart home I quickly look the display next to the door to double-check if all lights are really turned off.” (T1 blog)
After module one the first test-living phase T1 ended. Both test-residents of T1 reaffirmed that they enjoyed getting more knowledge of their electrical consumption and wished for a smart meter and feedback device in their own homes to test their appliance that were older than those in the smart home. In the long run however they wished for some financial motivation and expressed their interest to come back for another living-phase in order to experience dynamic pricing.

“It was like a great game here, but when I think about it I believe that a real objective only comes into play if the feedback is backed up by a financial benefit.” (T1 interview)

Module 2: Dynamic Pricing

In module two dynamic prices were added to the experimental set-up of T2. The first tariff in use was a day-and-night tariff with fixed time-zones between 8:00 and 20:00 hours. The test-residents demanded over 40% of their overall electricity demand during the low-price zone (20:00 to 8:00 hours); however this had already been the main time of consumption in their first week, when a static price signal was given. In line with this behavior, the test-residents also perceived this tariff as easy to integrate into their daily life.

“I think that we manage to use the night tariff pretty good. We try to wait until 8 p.m. to use the dish washer, the washing machine and the tumbler.” (T2 blog)

When the tariffs with more price-levels and a dynamic price scheme were introduced, the test-residents started to use the EMP in a different way. While it had been a feedback tool first, it was now mainly consulted as an information source for the electricity prices. In their point of view the price forecast for the upcoming 24 hours was the most important feature of the EMP. Furthermore they liked the price button that showed the current price level and accordingly changed its color (green, yellow, red).

“With a quick glance I was able to check the current price. It is quick and easy to comprehend with the three colors.” (T2 interview)

As a result they stated that they were more interested in the general price level (low, medium, high), as in the specific price. Therefore no remarkable difference between the tested price spreads was perceived. This can have various reasons: On one hand the bonus-malus system was designed in a way that load-shifting was rewarded independently from the price spread, therefore the spread itself had no direct monetary incentive. On the other hand the test-residents felt that the unit ct / kWh was difficult to value and thought that projecting the impact of the prices on the yearly electricity bill in real-time would be more comprehensible.

“To me it is difficult to estimate what 7, 22 or 37 cent mean. The price differences are not very big.” (T2 interview)

The test-residents needed some familiarization time with the dynamic price scheme. This required to check daily the upcoming prices and to manage the appliance use accordingly. The test-residents felt that this was interfering their daily plans, especially because one of them was working in shifts and had therefore very structured routines with only few ways of derogation. In order to cope with the varying electricity prices the test-residents looked for clock timers and some appliances indeed had an integrated one. From then on a couple of appliances were regularly used in the low-price zones – even if these occurred during the day when the test-residents were at work or at night-time. Contrary to the dishwasher, the washing machine was however not shifted into night times, because it was perceived as too noise-disturbing. The overall analysis (of the seven weeks in which tariffs were tested) reveals that the residents made best use of low-price zones, when they were at home: on Sundays. Figure 10 shows exemplified the use of the dish washer during one of the experimental weeks.
Over all weeks of T2 most electricity had indeed been demanded in low-price zones. The main reason for shifting the use of at least some appliance into low-price zones was motivated first by the experimental setting and the fun of trying to cope with the tariffs offered. Furthermore the bonus gathering had a motivational effect, too. Respectively cost saving was mentioned as the main reason to choose a dynamic tariff also for the test-resident’s households.

“I like the variable prices. If I could – let’s say – save at least 50 € per year, then I would choose it for my home, too. On the other hand 50 €, that is not even the price for one cocktail every month. Well, anyway if I can save, then I take it.” (T2 interview)

The shifting (resp. bonus) effects during the test-living phase were diminished by a remarkable amount of consumption at high-price times, caused by the same appliances over the whole test-living phase, those mainly being the ceramic stove top, coffee maker, kettle, lightning, stove, television and toaster. These appliances are – contrary to autonomous appliances such as the freezer – theoretically shiftable, but were not shifted by the residents due to their comfort and entertaining services. These “services” were mostly demanded on leisure days: Friday and Saturday.

“Especially activities like cooking are very difficult to shift. We have seen that the tariff was red, but still used the stove or the other kitchen appliances, because it was more important to us than the electricity price” (T2 interview)

A tariff with five price-levels was tested for one week at the end of module two and was accepted very well by the test-residents. Even though coordination was higher, the test-residents felt that they had more possibilities to consume electricity in low-price zones as there were two low-price-levels. Furthermore the five levels implied that the duration of each price zones was shorter – and thus waiting for a green zone didn’t take as long as with e.g. the two-level tariff. Indeed most electricity demanded at “green” zones was during the test of this five-level tariff with a rate of 48 %.

“I liked the tariff with five levels most, because it was good fun. There were simply more possibilities to use the appliances in between. During the day there were zones with 7 or 14 cent and thus more cheap times during the day.” (T2 interview)

Yet, both said that on the long-run it would be difficult to manually manage the use and set the clock timer of the appliances with such a dynamic tariff. Accordingly the test-residents preferred to have a less dynamic tariff in their own households. While one was undecided between a tariff with two or three price-levels, the other test-resident was more skeptical saying that he would stick to a static tariff if the low-price zones of the two-level tariff started too late in the evening than to make use of it. Willingness to choose a dynamic tariff at their own homes also depended on the supplementary equipment, especially a feedback and price information device, and its investment payback time.

When we asked them to suggest features that would help them to make better use of dynamic pricing in their everyday smart home life, they proposed some automated system that was intelligent enough to control the ap-
pliances according to the prices. In this way they would not need to keep track of the electricity price forecast as much. The test-residents were able to experience such an intelligent system in module three.

Module 3: Automated Energy Management System

Over the last two weeks of the test-living phase the automated EMS was activated that enabled the full use of the smart appliances, i.e. declaring a time frame so that the EMS programs and activates the use of the smart appliances according to the electricity prices within this time frame. The test-residents were impressed by this possibility and believed that it was helpful in their daily routine.

“Now that the automated EMS is activated, it is getting more interesting. I’m looking wide-eyed at the appliances when they just start-off.” (T2 blog)

However checking the EMP and setting the clock timer had become such a habit over the course of the test-living phase, that they first ignored the automated EMS. Even though they had wished for such a system before, they perceived it as technically complex and time-consuming to familiarize with it now. After a few days they then stopped setting the clock timers and scheduled the smart appliances over the EMS. The use of the EMP had changed at this point of the experiments again from a feedback and information source to an interactive man-machine interface. However, the test-residents did not completely trust the automated EMS and set their preferred time-frame every time before using a smart appliance in order to ensure that the appliances were scheduled in a low-price zone.

“I guess I have not used the smart appliances in the inventor’s intention. First I have always checked the price projection and only then set the time frame accordingly on the touch-screen display.” (T2 interview)

Table 3: Electricity demand in each price zone during the test of the three-level tariff with high price spread

<table>
<thead>
<tr>
<th></th>
<th>Manual use</th>
<th>Automated use</th>
<th>Automated use</th>
<th>Automated use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Week a</td>
<td>Week b</td>
<td>Week c</td>
<td>Week d</td>
</tr>
<tr>
<td>Low-price zone</td>
<td>30%</td>
<td>38%</td>
<td>42%</td>
<td>39%</td>
</tr>
<tr>
<td>Mid-price zone</td>
<td>35%</td>
<td>33%</td>
<td>29%</td>
<td>29%</td>
</tr>
<tr>
<td>High-price zone</td>
<td>35%</td>
<td>28%</td>
<td>29%</td>
<td>32%</td>
</tr>
</tbody>
</table>

Comparing the weeks with the three-level tariff between the manual and the automated use of appliances, it shows that a slightly better response to dynamic pricing was able (cf. Table 3); however no remarkable increase in load-shifting can be reported, as the appliances with smart functionalities were the same as those already shifted manually before (dishwasher, washing machine, tumble dryer). The exemplified load curve for one of the automated weeks still shows how well the test-residents handled the automated options of the EMS, as peaks can be observed right after a low-price zone is on (cf. Figure 11)

Fig. 11: Exemplified load curve with an automated use of smart appliances in T2
When thinking about smart appliances in general the test-residents thought that those three in the smart home (dishwasher, washing machine and tumble dryer) were the most suitable ones, even though they did not make use of the “smartness” of the washing machine and the tumble dryer. There was one main reason for resistance: the door of the washing machine did not open automatically after running (as in the case of the dishwasher) and the test-residents feared that the clothes would stay in the wet drum for too long, if the running time was scheduled by the automated EMS during absence of them. Therefore a combined appliance was suggested that started the drying right after the washing. One test-resident also suggested to equip the home with a smart refrigerator or smart freezer, as these were autonomous appliances and their control (i.e. scheduling their cooling time) did not interfere directly with other daily activities. A closer look at the total consumption over the eight weeks reveals that most electricity was demanded by the freezer with a share of nearly 24% and thus remarkable load-shifting could be possible with this appliance.

Before the T2 ended the test-residents were asked for their final evaluations and which of the smart home technologies experienced, they would like to have in their own homes. The test-residents came to different conclusions: one stated to immediately choose a dynamic tariff preferably with a feedback and display device as well as to propose the installation of a PV system to the household community. The other one either wanted to equip his home with all the technologies demonstrated or not to change anything. As he didn’t see too much potential for saving electricity at his house, he would need to go for load-shifting for a monetary benefit. However manual adoptions would be too time-consuming and therefore he would need an automated EMS, too.

“Well either feedback, dynamic pricing and home automation or nothing. A singular option doesn’t help me, because I would not adapt my behavior to dynamic prices at home in the long run. All these technologies are too expensive anyway, but maybe in the future, I can consider them.” (T2 interview)

6. Discussion and Conclusions

Summary and discussion of results

In this study, two experimental test-living phases with a total number of four test-residents were conducted with the objective to analyze the acceptance of smart home technologies in daily life. A smart home laboratory on KIT’s campus was used as a residential setting to provide technical innovations that enable load-shifting as well as electricity conserving: various feedback options, dynamic pricing, and an automated energy management system. These technologies were tested in a modular way in three different phases and were accompanied by different surveys.

In our study direct feedback options in real-time (in-house displays) were more effective than indirect ones (enhanced billing) with regard to increasing awareness for electricity. In general, the test-residents showed high interest for detailed information on their electricity consumption and therefore intensively made use of the feedback functionalities. However, no electricity conservations were induced by the feedback itself. A display with real-time data on electricity prices became the crucial source of information, when dynamic pricing was introduced to the experiment. Motivated by the experimental set-up and bonus gathering possibilities, the test-residents tried to adapt their electricity demand to varying price levels, but needed some familiarization time. Dynamic pricing turned out to be overall effective in increasing the effort of shifting at least some loads. Those activities that ensured comfort and entertaining services were hardly subject to shifts. Moreover, the test-residents reported that the dynamic prices required a time and effort, when planning daily activities. One strategy employed was the use of some clock timers, but this still required to check prices regularly. Therefore the test-residents wished for an intelligent automation system that was introduced later during the experiment. Impressed by the technical possibilities and complexity at the same time, some familiarization time was again needed to make full use of automating the smart appliances. In our study the functionalities of the automated EMS didn’t increase the amount of electricity shifted, but ensured more convenience in doing so. The test-residents confirmed that in the long-run automated options were needed – especially if electricity prices were highly dynamic. For their own homes, the test-residents reported interest for the smart home technologies under the precondition that the investment in those was shortly paid back and maintained high levels of comfort. The motives for accepting or refusing smart home technologies in daily life abstracted from the experiments can be broken down to four key drivers: technological orientation, price, ecology and convenience (cf. Table 4).
Table 4: Main motifs for the acceptance of smart home technologies in daily life

<table>
<thead>
<tr>
<th>Incentives</th>
<th>Barriers</th>
</tr>
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<tbody>
<tr>
<td>Innovative technology</td>
<td>Complexity of technical equipment</td>
</tr>
<tr>
<td>Cost-saving potential</td>
<td>Long payback time</td>
</tr>
<tr>
<td>Integration of renewable and self-generated electricity</td>
<td>Cognitive effort</td>
</tr>
</tbody>
</table>

Bearing the sample structure in mind (interested in energy-related topics, open-minded for new technologies, heterogeneous with regard to daily life routines) the analysis of the results is particularly interesting. Even in this sample the test-residents had little knowledge about their electricity consumption patterns before moving in, but reported having fun exploring it. While this reveals again the particularity of electricity, it points out that interactive solutions that enable to experience electricity consumption in a remarkable way, can face the challenge of marketing electricity services. The involvement towards feedback decreased over time during the test-living phase and monetary savings – when perceivable – became more important, which was also one of the main underlying motives in using the smart home technologies and in shifting loads. However it became clear several times over during the experimental periods that the acceptance of load-shifting was limited by various factors. (1) Not all daily activities and routines are shiftable, e.g. when working hours collide. (2) If some activities are shiftable in theory, they are not necessarily subjected to shifting, because they deliver comforting and entertaining services. This again points out that electricity is not demanded as an independent good, but as an enabling service (cf. van Vliet et al. 2005) and adoptions regarding having a warm meal or enjoying a movie are harder to make. (3) Other activities that involve the consumer less, like washing clothes, are fairly easy to perform at another time of a day. Yet the technical equipment itself can be a barrier, as occurred during the test-living phase with automating running times of the washing machine. (4) The last limiting factor observed in this experimental study was the challenge to keep motivation and involvement high. In order to maintain the “willingness to shift” in a comfortable way, using smart appliances through an automated EMS were introduced.

While the innovativeness of smart home technologies were the key driver for their acceptance during this experimental study, the test-residents would probably not be willing to spend the same amount of time to familiarize with the technical equipment in their own households. Therefore convenient solutions and a customer-friendly support are recommended in order to allow acceptance of these technologies by a broader consumer base. Further value-added features (such as security) can increase their attractiveness, too. Regarding the energy-related elements we recommend that future smart home solutions satisfy the consumers’ desire to get easy and simple advice on how to save costs, provides cost-saving potential, secures high levels of flexibility and an easy integration in everyday life.

Limitations

As with all empirical work, this study is subject to several limitations. Certainly, the generalizability of the findings is limited. The test-residents recruited for this experiment are not representative for any kind of population. Moreover, they signed up voluntarily, so views and experiences of individuals not interested in this kind of technology are not covered here. When recruiting test-residents we deliberately tried to engage individuals who are likely to be among the early adopters.

While the KIT’s smart home offers a unique residential setting, this is also a limitation because smart home environments that are designed differently and have different appliances may also elicit different behaviors. As the technologies tested require a lot of technical and measuring equipment in the front- and back-end that is not available on the market yet, it was impossible to conduct the experiments with a control group. Therefore direct comparisons to any other households are limited.

Even though the test-living phases were fairly long for being an experiment under laboratory conditions, no conclusions can be made on the long-term effects and behaviors. Furthermore, the experimental phases were not long enough to exclude familiarization effects with the setting and the high-end appliances in the metered data.

While the modular experimental set-up was appreciated by the test-residents, another set-up could lead to other results. This is also true for the bonus-malus system that was used as financial incentive. Furthermore the value
of the bonus points (0.5 EUR / bonus point) was higher than the real value of the electricity price. While the test-residents earned 42 bonus points (21 EUR), their real savings would have been a fraction of that (2.47 EUR).

Conclusions
Our study sheds more light on the acceptance of smart home technologies in everyday life. It turns out that when these technologies (feedback, dynamic pricing, automated energy management system) are used, load-shifting efforts are observable. The incentives for this load-shifting behaviour are monetary savings, the use of renewable energy resources and of innovative technologies.

Load-shifting potentials might even increase if BEVs experience a market penetration. Therefore, further analyses on the acceptance of shifting car-charging and integrating the car battery into the energy management system (e.g. in combination with the PV system) seems worthwhile. Since monetary benefits were stated to be a central driver for adoption, further research on consumer preferences regarding different tariff models, such as load-dynamic tariffs, as well as their use in everyday life (also with a BEV) can be interesting. In order to challenge this study’s results further experiments with other target groups, such as business consumers in smart offices, are needed.

Based on the results of this study we recommend that policies take these behavioral influences on electricity demand of residential consumers into account. Greater transparency on demand and costs are an incentive in the short run (and smart meters might therefore be a good starting point), but in the long run additional benefits have to be perceivable – such as monetary benefits and a sustainable environmental impact. These incentives that go beyond feedback will enable the acceptance and diffusion of smart home technologies, and are therefore decisive on our progression towards a more efficient energy system.
7. References


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