Demand Response with Smart Homes and Electric Scooters: An Experimental Study on User Acceptance

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ABSTRACT

Smart technologies and electric vehicles are supposed to efficiently use renewable resources by shifting loads and storing surplus electricity. Although several field tests with smart meters, dynamic pricing or electric vehicles are conducted, hardly any consumer has experienced a combination of these components. So far, neither consumer perceptions nor the effectiveness of these demand response options are apparent.

Test-residents were selected to move into KIT's smart home for several weeks. It is equipped with smart appliances and two e-scooters. An energy management system schedules EMS) the operation time of appliances according to external price signals. Everything can be monitored on touch-screen panels provided in every room and on mobile devices.

In this experimental setting demand response was tested in four phases: First, test-residents were provided with feedback. Then, different electricity-tariffs were introduced. Finally, the test-residents were able to fully use the EMS to schedule operation times of the smart appliances automatically. Electric scooters were provided for free use during the whole period.

In general, the test-residents showed high interest in detailed information on their consumption. However, feedback alone had neither load-shifting nor conserving effects. These actions were realized when dynamic pricing was introduced. The willingness to shift consumption was limited to a few appliances (e.g., dishwasher) and depended on monetary savings. Charging the electric scooters was only shifted, if there was another vehicle available for emergencies. The automatic load-management ensured more convenience in shifting demand, especially in combination with dynamic electricity prices and load-limits.

Introduction

The aim of reducing greenhouse gas emissions by 80% in Germany by 2050 with respect to 1990 causes major changes in the energy sector: electricity is increasingly generated from renewable resources, that are partly volatile, hardly controllable and to some extent generated decentralized. This challenge might rise with an increasing electrification of the transportation sector, as electric vehicles (EV) will raise peak loads presumably in the evening hours. Different measures that tackle these challenges are under discussion and include demand response. The aim is to match electricity demand with (renewable) supply by incentivizing households to respond accordingly. This implies some adaptions to everyday household behavior, e.g., charging the EV at a different time of the day. However, promoting the sustainable use of electricity is particularly difficult, because it differs from other goods: It is invisible, untouchable, and only consumed indirectly via related activities (Hargreaves, Nye & Burgess 2010). Providing households with feedback, offering a price incentive and equipping them with automated solutions might help to shift loads.

Some of these measures have been addressed in European and German Policy (directive 2006/32/EC, §§21, 40 German Energy Act): utilities have to offer some kind of electricity tariff that motivates residential consumers to conserve electricity and/or shift their demand. Furthermore, new buildings have to feature smart meters given their feasibility. However, the number of German households that are actually equipped with a smart meter, accompanying display products or have a dynamic electricity tariff is still very low. Only few smart appliances are being offered on the market and their technical integration into some kind of household management system is under research. So hardly any consumer has experienced a "smart" future household environment on a daily basis, and therefore neither the user acceptance nor the effectiveness of these solutions is clear. At the same time market penetration rates for EV are still low, only representing 0.02% in the car, 0.08% in the scooter, and 5% in the bicycle market (KBA 2011, ZIV 2011). Thus, there are only few EV-users and even less that have additionally experience with demand response.

In order to evaluate demand response we have analyzed the everyday electricity demand of test-residents in a smart home with electric scooters (e-scooters). The load-shifting potential of the smart home solutions was tested in four phases: 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 test-residents. Then different electricity tariffs were tested. Afterwards an automated energy management system (EMS) was introduced that enabled the smart appliances to react automatically to dynamic prices. Two e-scooters were provided for free use during the whole period. The test-living phase was accompanied by two in-depth interviews, a pre-post-questionnaire and an online blog.

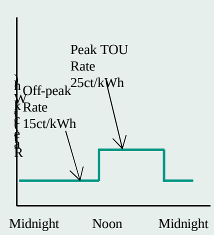
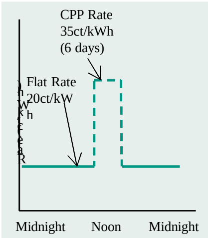
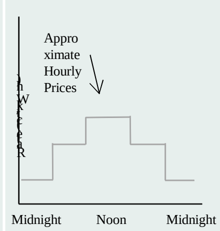
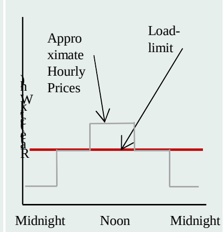
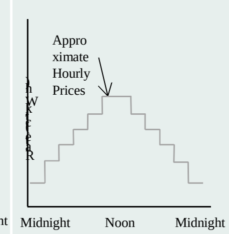
The paper is organized in five sections: First we shortly summarize the state of research. Then, we describe the smart home setting and explain the research design, before presenting the results. We close with a discussion of our results.

Previous Research

The main assumption behind most technologies introduced to field trials is based on an information deficit model (cf. Hargreaves, Nye & Burgess 2010): It is assumed that consumers lack awareness of their electricity consumption due to its "invisibility". If consumers therefore had enough information, they could be able to change their demand. Feedback is therefore a popular element with smart meters. The findings about energy response, i.e., decreasing energy demand, after introducing feedback systems are mixed: While Darby (2010) indicates that energy conservation of 5–25% are possible in her review, marginal to zero effects were reported in other studies (cf. Pyrko 2011).

From a micro-economic point of view, offering a financial incentive leads to optimal behavior of households, as they are (financially) better off by consuming less at times of high electricity prices. Results from some field tests confirm this theory, as the effectiveness of feedback picks up with financial incentives leading to lower electricity bills (cf. Chassing & Kiesling 2008). This 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). 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 (EEE 2006). A meta-review of VaasaETT (2011) reveals that not all dynamic pricing models have the same effectiveness: while Time-of-Use Tariffs (TOU) lead to an average load-shifting effect of 5%, Critical Peak Pricing (CPP) models proved to be most effective (16% less loads during peak priced hours). Figure 1 provides an overview of how the different pricing models can be classified.

Figure 1. Classification of electricity pricing models

Parameter	Exemplary TOU (time-of-use pricing)	Exemplary CPP (critical-peak pricing)	Exemplary RTP (real-time pricing)	Exemplary RTP with load-limit	Exemplary „extreme“ RTP
Number of price levels	Two	One	Three	Three	Infinite
Time scheme	Each level valid twelve hours with fix scheme (prices apply at same times every day)	Flate price applies everyday (fix scheme)	Each level valid at for one hour with dynamic scheme (structure changes daily)	Each level valid at for one hour with dynamic scheme (structure changes daily)	High dynamics, as consumer prices follow market prices
Load-limit	/	/	/	3 kW	/
Critical peak event	/	6 times per year	/	/	/
Electricity price	15 – 25 Ct/kW	20 Ct/kWh; additional penalty (+15 Ct/kWh) when CP-event is called	15 – 20 – 25 Ct/kWh	15 – 20 – 25 Ct/kWh; additional penalty (+ 5 Ct/kWh) when passing load-limit	Can adopt any price between 10 Ct/kWh and 35 Ct/kWh
					

Based on Fox-Penner 2009

Residential consumers, however, don’t seem to be very open to behavioral changes in daily routines and require that demand response options should not be linked to reductions in comfort (cf. Paetz, Dütschke & Fichtner 2012). Consumers therefore indicate high acceptance of smart appliances and perceive home automation systems positively.

This also seems to be true for electric mobility. During a German field test with battery electric vehicles (BEV) dynamic pricing had been introduced, but had little to no effects (Paetz, Jochem & Fichtner 2012). However, all car users reported their willingness to drive emission-free and thus charge ‘green’ electricity. The idea of having a smart charging station that charged at low-price times automatically was thus highly accepted.

To sum up, the current literature suggests that demand response options have the potential to support (some) reductions of peak-loads with higher effects when combining dynamic pricing with feedback. Regarding user acceptance, the literature indicates that consumers show positive reactions when confronted with automated solutions.

As literature findings do not allow formulating concrete hypotheses, this study takes an experimental approach looking for first-hand user response to a smart home & mobility environment: How are smart technologies used in daily life? Which elements prove to be effective? What drives their use? Is demand response applicable for electric mobility?

Research Design

Smart Home Setting

In order to answer these research questions outlined above an experimental approach in a smart home laboratory was employed. The KIT smart home[1] represents a building for two residents, which consists of a 60 sqm two-bedroom apartment and a 20 sqm equipment room. A PV-system is installed on the roof and two e-scooters are integrated over a charging station.[2] The kitchen is equipped with smart appliances (washing machine, dish washer, tumble dryer) that are connected to a central communication gateway that provides data on the status of each appliance and is able to receive control signals. All appliances (smart and conventional) are monitored and integrated to the EMS.

Based on the electricity price information the EMS is able to schedule the smart appliances automatically within certain limits. These limits reflect the residents' preferences, which he/she can set by specifying a time frame in which the appliances may run (degree of freedom). The EMS then calculates the most cost-effective running time and communicates it to the user on Energy Management Panels (EMP) that serve as a connection between the EMS and the user. It displays relevant information and actions of the EMS and is provided on four touch-screen displays and a mobile device (iPod Touch).

Two e-scooters are integrated to this smart home environment. These are Elmoto scooters of type HR2 with a wheel hub motor and a maximum speed of 45 km/h. Recharging the lithium-ion battery (1.1 kWh) it takes up to six hours at 350 W. E-scooters can be driven on all German roads, except for highways, and need an insurance indicator.

Experimental Set-Up

Three test-living phases have been conducted in this setting (cf. Figure 2). This paper focuses on T3, as the results of T1 and T2 have been published in Paetz et al. 2011. The experimental set-up is structured into four modules 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.

Figure 2. Experimental Set-Up of test-living phases in the smart home

Module	Test	T1 (4 weeks)	T2 (8 weeks)	T3 (5 weeks)
1	Feedback	✓	✓	✓
2	Dynamic Pricing	/	✓	✓
3	Automated EMS	/	✓	✓
4	Electric Mobility	/	/	✓

[1] The term "smart home" is used for linking different household devices to a network. The term can therefore include aspects of ambient assisted living, entertainment, and security. Here we focus on energy management.

[2] Thermic devices (µCHP, cooling ceiling) and a mobile storage (BEV) were not yet implemented in this study.

The objective in module one was to analyze the effects of feedback on electricity demand. The feedback was provided by the EMP. Thus the residents were able to check the load of the household and of each appliance, as well as the PV-power in real-time. The electricity price was also displayed, but was kept static during the first module. In module two several dynamic pricing models were introduced (cf. Figure 3). All tariffs were calculated with an average price of 22 Ct/kWh. While we tested a variety of TOU and RTP tariffs in T2 experimenting with time schemes, price levels, and spreads, we used just one type of RTP in T3. In week three we added a load-limit to it, meaning that a penalty applied for demand above this limit. During the last two weeks (module three) the automation functions of the EMS had been activated and the full use of the smart appliances was possible. Both e-scooters (module four) were available for free use during the whole period.

The test-residents did not pay any rent or expenses on energy. In order to offer them an incentive a bonus-malus system was designed. For each kWh consumed in the lowest price zone, the test-residents received one bonus point – vice versa a malus point for each kWh in the highest price zone as well as above the load-limit. Each bonus point correlated to € 0.5 and the value of the bonus balance was disbursed at the end of the test-living phase.

Figure 3. Dynamic pricing models tested in T3

Tariff structure	Standard	TOU	RTP	RTP	RTP	RTP with load-limit		
Time scheme	Fix		Dynamic					
Load-limit	/	/	/	/	/	6 kW	4 kW	varying: 2.5 – 6 kW
Price levels	1	2	3	3	5	3	3	3
Prices [Ct/kWh]	22	12 28	17 22 37	7 22 37	7 14 22 30 37	7 22 37	7 22 37	7 22 37

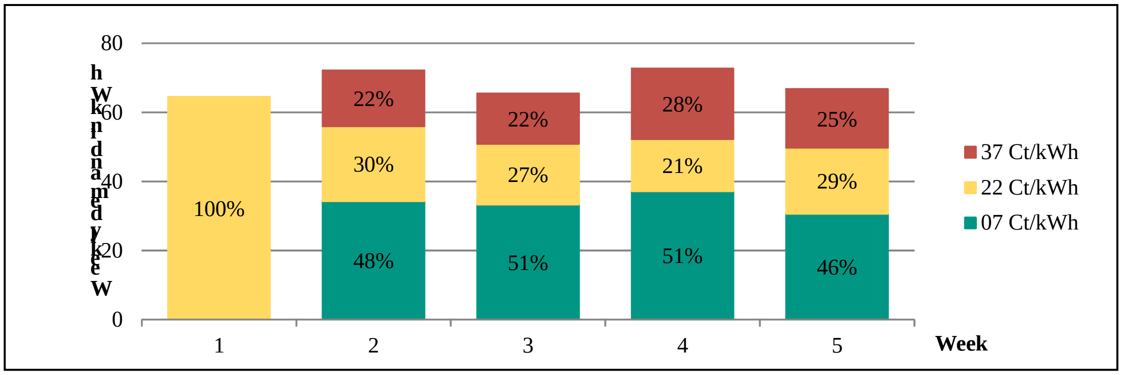
Methodology and Sample

The experimental design does not allow gaining representative results, thus selecting test-residents is an important step. We recruited a young sample (22-31 years), that was selected with a screening questionnaire that aimed at finding those who were generally interested in the topic, but had little knowledge and no experience with the technologies under research. Final selection took place after a house tour. While T1 was carried out with two students, two "average adults" (=non-students) lived in the smart home during T2 and a mixed group (one student, one non-student) was recruited for T3. Besides the screening questionnaire and a short standardized pre-post-questionnaire (on attitudes), we conducted two in-depth interviews – a method to explore opinions allowing close interaction with the researcher and the technology. During the test-living phases the residents were able to write about their experiences in an online blog. With the combination of these survey types we gained a rich amount of data in the participants' own words. This qualitative data was analyzed together with quantitative behavioral data from the real-time metering.

Results

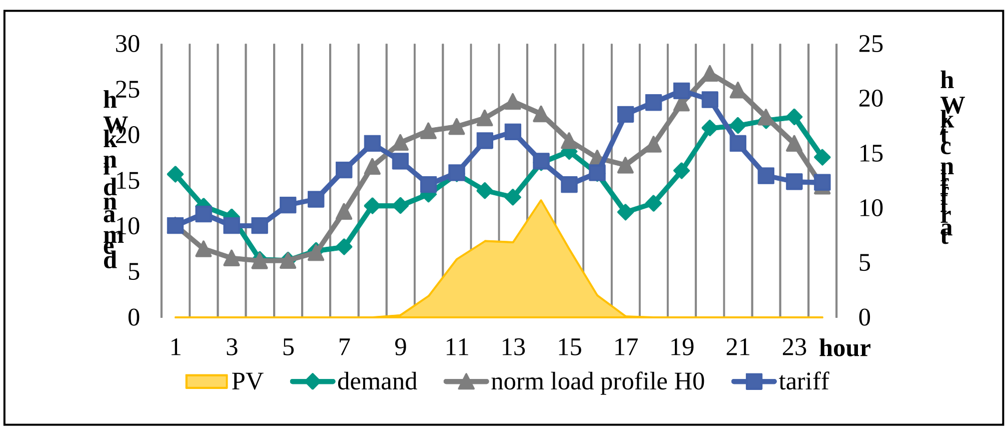
The average electricity demand during the test-living phase was 68 kWh/week. Across all weeks the test-residents managed to consume around 50% of their electricity demand at low-price (7 Ct/kWh) times and the other 50% more or less equally split up at mid-price (22 Ct/kWh) and high-price (37 Ct/kWh) times (cf. Figure 4). The functionalities of the automated EMS (in weeks four and five) did not increase the demand during low-price times. For two reasons: Firstly, the test-residents were able to adjust their energy use well manually to dynamic pricing. Secondly, they shifted the same appliances during the "manual" weeks as those controlled by the EMS.

Figure 4. Electricity demand split into price levels



By comparing the average daily load-curve accumulated over the five weeks with the German norm load profile (H0), a quite similar load structure is visible during the day (cf. Figure 5). Both peaks (around noon and in the evening) occur later indicating a load-shift. By adding the price curve over that period, a reverse effect between electricity price and demand for the test-living profile can be observed, leading to an electricity bill reduction of 6.5%.

Figure 5. Accumulated demand and pricing in comparison to normal load profile



In the following we present the results of each module and illustrate them with interview statements, blog posts as well as their behavioral data[3].

Module 1: Feedback

Especially during the first days the test-residents made extensive use of the touchscreen panels. They had fun analyzing the consumption and confirmed that real-time feedback leads to a more sensitive use of appliances. The test-residents were fascinated by the real-time information on the PV-power generation. As T3 took place during the winter period, they were a bit disappointed that they were not able to consume more of the self-generated power (cf. Figure 5).

"The touchpads are easy and fun to handle. I'm personally very interested in the PV power. Luckily, we are connected to the grid, because otherwise we would sit a lot in the dark."

There were some additional applications on the EMP. The weather forecast and the remote light control were appreciated most. The test-residents even thought that these were crucial for having some kind of feedback device at their own homes and had many ideas for additional applications (e.g., roller shutter control).

A weekly bill provided information on the electricity costs, the charging loads and a comparison of consumption with an average German household. Although one test-resident did not like the comparison, the other test-resident thought it was useful and was surprised that their consumption was not lower than the German average.

After using each appliances a few times, they felt they knew their demand quite well, so there would be no new feedback information, unless a new device was introduced. Furthermore, they saw their electricity demand as given and had no intention reducing it.

"After using the washing machine twice, I know its consumption. We consume electricity anyway. I'm not going to stop washing my clothes only because I see how much is required for doing so."

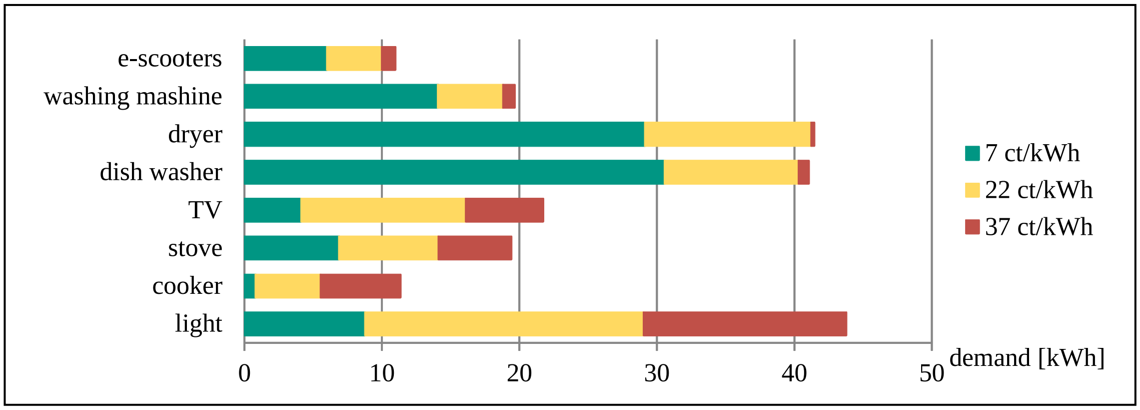
Module 2: Dynamic Pricing

The introduction of dynamic prices changed the use of the EMP and the devices. The test-residents checked the price forecast in the mornings and planned the use of the appliances accordingly. Splitting the overall demand into the single devices allows analyzing which appliances were used at the different price zones and shifted accordingly (cf. Figure 6). This was especially the case for appliances with time-independent use, e.g., the dish-washer. Appliances with a high share in the red price zone show an inconvenient load-shift over time. Not surprisingly, those appliances are light, cooker, stove, and TV. For their comfort and entertainment services the willingness to subject these activities to dynamic pricing was low. We classify them as appliances with immediate use pattern and low shifting potential. In contrast appliances classified as permanent or time-independent are suitable for (automated) load-shifting, since they have high electricity demand and low timing constraints. As an example the test-residents said to be able to postpone the dish-washer use by twelve hours without constraints

[3] All statements have been translated into English while retaining the gist of the original German.

in their daily routines. From their perspective the dish-washer was the most suitable, the coffee-machine and the stove the least suitable devices for subordinating dynamic prices. Furthermore they wished for a smart freezer that would automatically plan its cooling periods according to the prices and allow cost savings in a comfortable way.

Figure 6. Electricity demand of certain devices split into price zones



The time scheme of the RTP also influenced the ability of the test-residents to shift appliance use. If low-price or mid-price zones applied on the brink of a day, it was perceived as too early or too late as to comply with them.

"This weekend we were very flexible and thus tried to use the appliances at low-priced times. Only on Sunday evening the green zone started after 7 p.m. and we were not able to wait with cooking for our guests until that time. Let's see how we will manage during the week! For sure I will not get up before 6 a.m. to brew coffee with cheap electricity."

In week three we added a load-limit to the RTP that was visualized on the EMP with a separate bar. During their activities the test-residents checked to see if they were able to use further appliances without surpassing the limit. In weeks three and four we had kept the load-limit fixed at 6 kW and 4 kW respectively. These limits had hardly any impact, being only violated during four minutes in each week with a total demand below 0.1 kWh. When starting to vary the load-limit down to 2.5 kW, the limit became significant. Even though, the amount violated had no effect on costs with a demand of 0.65 kWh, the violation time jumped up to 87 minutes. This low limit was not accepted very well and the appliances used anyway.

"Until 3.5 kW it's fairly manageable to use the appliances time-delayed, but beneath that it's impossible. The stove alone violates the limit. As long as there's no shortage, we can put up with the penalty."

When asked about their preferences for dynamic pricing models for their own homes, both test-residents refused to have one with a load-limit, as they felt it was too constraining. So they were in favor for the RTP, even after showing them a TOU model. RTP would allow using some appliances also during the day and one would not be forced to wait until the quite static TOU price at night. Furthermore, one of the test-residents felt that he would better get his share of low market prices than with yearly pre-calculated TOU prices. CPP models were not accepted at all, as the test-residents felt, that utilities should be able to forecast the main influences on costs and there should be therefore no need in calling critical events. Furthermore, both residents felt that price levels should be somehow subject to a cap, fearing that if there would be no wind power generation over the course of several weeks, prices would stay constantly high. Not only did they feel that it would be unfair, but also difficult to save on the electricity bill. In line with the willingness to save money, higher price spreads were preferred to lower price spreads, as long as there was a cap on the highest price zone.

"If the price differences were only 2 Cents, it wouldn't matter. There would be no motivation at all. I'd then rather turn on immediately the tumble dryer than waiting and saving 4 Cents. But when we talk about 20 or 30 Cents, I would really take care about that."

The cost-saving expectation was around € 150/year. Although this expectation is similar to previous research results (cf. Paetz, Dütschke & Fichtner 2012), it is fairly high. During this test-living phase the residents saved around 6.5% on electricity costs. Projecting this to a complete year the savings would be around € 63.

While saving costs was the main driver for one test-resident to adopt his demand to electricity prices, ecological issues were central for the other test-resident. Especially the idea of using renewable energies – preferably from the own PV – was appealing. Accordingly, she wished for more information about the generation mix of electricity.

Module 3: Automated EMS

In weeks four and five the automated EMS was activated and enabled the full use of the smart appliances. So far the test-residents had managed to comply with dynamic prices very well, because they discovered and used the time-clockers integrated in some appliances. They did not switch right away from this manual strategy to the automated EMS. While the automated EMS also considered the load-limits when setting the smart appliances, this was a mathematical task in the manual case. Thus, the options of the automated EMS were used regularly, although the test-residents didn't fully trust it and cross-checked, if it had set the appliances correctly.

"I usually set the automated EMS first and check if it delivers viable running times for the appliances. Otherwise, I stop it and set them again manually."

The automated EMS was mainly set for the dish-washer and the washing machine. Even though, the tumble dryer had the smart functionalities, too, it was not used much, as the test-residents feared to leave the wet clothes in there for too long, before the program would start. When thinking about further appliances that would be suitable for the automated program, one test-resident thought of EVs.

"The automation would be ideal for an electric car. It could for example be charged in between two peaks of the washing machine. Household appliances have to run through, but the charging of the car could be interrupted. The automation makes most sense for cars."

Module 4: E-Scooters

The objective of providing the e-scooters was to analyze the acceptance of the e-scooters itself and the effect of demand response on the charging behavior. As Figure 6 shows, the e-scooters did not represent a high share of the total electricity demand. Still, they were mainly charged during low-price times. Similarly to the other household appliances there was a high willingness to shift the charging process, but late times limited to put this into action. In addition the charging plugs were outside, which limited this action even more.

"Generally I tried to comply with the prices, but yesterday for example the low-price was only on at mid-night and that was too late. Some kind of clock-timer or even the full automation would be great, because it is annoying to go out again and plug the scooter in."

Instead of plugging the e-scooters immediately after arriving to the smart home, one test-resident tried to wait until a low-price time and if she didn't manage, she took the other e-scooter. This strategy was possible, because she was the main user. Apart from a few exceptions the other test-resident stuck to using his car.

"I have not found the ideal application for the e-scooter. Maybe because I was never used to riding a scooter or a motorcycle? Within the city I prefer to walk and for longer distances I use my car. Most of the times I also carry things with me and the e-scooter has only limited capacities for that."

The main user rode the e-scooter every morning to go to work and enjoyed not arriving as sweaty as with the bicycle. In the afternoon she used it to get to her sports activities. According to her perception her mobility patterns did not change apart from the fact that she was now using the e-scooter instead of her bicycle. However, the feeling of riding the e-scooter was quite different. While she enjoyed the fast acceleration, she felt limited not being able to ride faster than 42 km/h, especially on state roads. Furthermore she felt that many pedestrians did not respect her right of way. In contrast to that the car drivers paid a lot of attention and were very interested in this electric vehicle.

"E-scooters are still a new thing in traffic and people react quite differently. Most are interested and approach me with questions. Others don't seem to take me seriously on that vehicle – maybe because it's so quiet?"

In order to make the e-scooter a more attractive vehicle, the test-residents suggested many improvements. Some consider the vehicle itself, such as having flashing indicators (instead of indicating by hand), other ideas consider the battery. Having an additional battery in exchange would increase the flexibility also with regard to dynamic pricing. Shorter charging times would make charging out of home (e.g., at the gym) more attractive.

Before T3 ended, the test-residents were asked for their final evaluations of the technologies and which, if any, they would choose for their own homes. Both said they would like to have a dynamic electricity price with some kind of feedback device that should not be too expensive. Although they thought that the other possibilities with the automated EMS and the smart appliances were interesting, it would be too cost-intensive to install them in already existing homes.

Discussion and Conclusion

Summary and Discussion of Results

In this study an experimental test-living phase was conducted with the objective to analyze the acceptance of smart home technologies and e-scooters 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: two feedback options, dynamic pricing, and an automated energy management system. These technologies were tested in a modular way 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 use. In general, the test-residents showed high interest for detailed information on their electricity consumption. However, no electricity conservations were induced by the feedback itself. Touchscreen 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 the bonus-malus system, the test-residents managed to adapt most of their electricity demand to dynamic prices and load-limits. Dynamic pricing turned out to be overall effective in increasing the effort of shifting at least some loads. One strategy employed was the use of clock timers. In order to respect the load-limits in a comfortable way the test-residents made use of the automated energy management system that controlled the use of the smart appliances (dish-washer, washing machine, tumble dryer). In our study the functionalities of the automated EMS didn't increase the amount of electricity shifted, because it applied to the same appliances that were shifted manually beforehand. However, the test-residents confirmed that in the long-run automated options were needed – especially in combination with electric vehicles. For their own homes, the test-residents reported interest in dynamic pricing (with a strong preference for RTP over TOU or CPP models) and some simple form of feedback device that wouldn't cost too much. Accordingly the central motifs behind the load-shifting efforts were cost-saving potentials as well as the use of (self-generated) renewable power.

Bearing the participant selection 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 "interested" sample the test-residents had little knowledge about their electricity consumption patterns before moving in and reported having fun exploring it. This points out that interactive solutions that enable users to observe their own electricity consumption face the challenge of marketing electricity services. The involvement with the feedback function decreased over time during the test-living phase and monetary savings became more important, which was also found to be one of the main underlying motives in shifting loads. Results show that the dish-washer, the washing machine and the e-scooters were the devices mainly subjected to load-shifting. As these appliances also represent a high share of the overall household electricity demand, they are most suitable for load-shifting. However the acceptance of load-shifting was limited by various factors. (1) Not all daily activities and routines are easily shiftable, e.g., when working hours collide. (2) If some activities can be shifted, they are not necessarily subjected to shifting, because they deliver comforting, entertaining, or mobility services. This again points out that electricity is not demanded as an independent good, but as an enabling service and adoptions are harder to make.

(3) Other activities that involve the consumer less, like using the tumble dryer, are fairly easy to perform at another time of a day.

While the innovativeness of the smart home setting was appreciated 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 a heating control) can increase their attractiveness, too. We recommend that future smart home solutions satisfy the consumers' desire to get easy and simple advice on how to save costs, provides information on the energy-mix, and secures high levels of flexibility.

Demand response is especially suitable for electric vehicles due to the required charging power, energy volumes of their batteries, and the long parking times. For these reasons further application areas for electric vehicles have to be found and marketed, if a higher share of electric vehicles is to be on our roads. This is especially important with regard to charging management options.

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, it is also a limitation, because different set-ups may also elicit different behaviors. This is also true for the bonus-malus system. The value of a bonus points was higher than the real value of the electricity price. While the test-residents earned 33 bonus points (€ 16.5), their real savings would have been a fraction of that (€ 4.76).

As a lot of technical equipment in the front- and back-end that is required, but not yet available on the market, 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 phase was fairly long for being an experiment under laboratory conditions, no conclusions can be made on the long-term effects and behaviors.

Conclusions

Our study sheds more light on the acceptance of demand response with regard to smart homes and e-scooters. It turns out that when smart technologies are used, load-shifting efforts are observable. The incentives for this load-shifting behavior are monetary savings and the use of renewable energy resources. We further looked at the use of e-scooters in this environment and can confirm load-shifting efforts for the charging process, too. Automated solutions, that enable load-shifting in a comfortable way, become even more important in combination with e-scooters.

Load-shifting potentials might even increase if electric vehicles experience a market penetration. Therefore, further analyses on the acceptance of shifting car-charging and integrating the car battery into the EMS (e.g., in combination with the PV system) seems worthwhile. Besides the electrical components also thermal components could be integrated into the EMS, as energy conserving and monetary savings are highly probable. In order to challenge this study's results further experiments with other target groups 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 savings and a sustainable environmental impact. These incentives that go beyond feedback will enable the acceptance of demand response, and are therefore decisive on our progression towards a more efficient energy system.

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