Conversations with my washing machine: an in-the-wild study of demand-shifting with self-generated energy

Conference or Workshop Item

Conversations with my Washing Machine:

An in-the-wild Study of Demand Shifting with Self-generated Energy

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ABSTRACT
Domestic microgeneration is the onsite generation of low- and zero-carbon heat and electricity by private households to meet their own needs. In this paper we explore how an everyday household routine – that of doing laundry – can be augmented by digital technologies to help households with photovoltaic solar energy generation to make better use of self-generated energy. This paper presents an 8-month in-the-wild study that involved 18 UK households in longitudinal energy data collection, prototype deployment and participatory data analysis. Through a series of technology interventions mixing energy feedback, proactive suggestions and direct control the study uncovered opportunities, potential rewards and barriers for families to shift energy consuming household activities and highlights how digital technology can act as mediator between household laundry routines and energy demand-shifting behaviors. Finally, the study provides insights into how a "smart" energy-aware washing machine shapes organization of domestic life and how people "communicate" with their washing machine.

Author Keywords
Microgeneration; domestic computing; sustainability; user studies

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interface.

INTRODUCTION
Distributed electricity generation and microgeneration is considered an important part of the future energy strategy [20]. Although the adoption of solar photovoltaic systems (solar PV) is slow, it means that ordinary householders have the potential to produce their own energy, as alternatives or supplements to traditional centralized grid-connected power. Evidence is beginning to emerge that households with solar PV exhibit saving behaviors intended to maximize the use of local energy and to minimize the use of imported grid energy [16, 17]. These behaviors translate a natural engagement into "*demand-shifting*" – a particular form of behavior change where energy consumption is shifted towards times of the day when local production is at its highest, thus using "green energy". However, this process is time consuming and requires gathering information from multiple sources, not always available or difficult to access (such as instant consumption, generation, export, and weather forecast).

In this paper we explore how an everyday household routine – that of doing laundry – can be augmented to help households with local solar energy generation to make better use of the energy they are producing. This is done by pulling together data from a range of devices and sensors – and by providing residents with suggestions on when to do their washing in order to maximize the use of locally generated "green" energy and minimize the use of grid energy. The project involved eighteen UK households with solar PV on their roof over eight months. We developed and deployed four different technological interventions mixing energy feedback, proactive suggestions and direct control to explore the role of technology as mediator between household laundry routines and energy demand-shifting behaviors, and investigated notions of automation, interactivity, feedback and control: How can users make best use of the information and control available? How do residents want their information to be brought to them? Do people want to receive a message from their washing machine to let them know when would be a good time to put the washing on – or should this process be more invisible, and be taken care of by the washing machine itself making the decisions?

In the remainder of the paper we first survey literature on domestic energy and digital home technologies aimed at reducing energy consumption. This is followed by a description of the study methodology and the design of four technology interventions. Finally, we present our findings gained from a combination of longitudinal data analysis and in-depths interviews.

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BACKGROUND

Routines and Behavior in Solar PV Homes

A number of studies have shown that with the introduction of solar power on people's roofs, householders are not just using more green energy, but are also changing their attitudes and behaviors towards energy and are beginning to ask questions about their own routines. Keirstead found in interviews with solar PV householders that they had become more aware of making small changes, such as turning off lights and unplugging appliances [17]. This finding is resonated by Hondo and Baba who report on similar energy behavior changes in solar PV households that they interviewed, but also noted an increased level of communication about energy within these households [16].

An in-depth study of several very green households, which had undergone substantial energy preserving modifications, showed that people also derive intrinsic satisfaction from energy preserving activities [29]. New routines, such as the daily job of opening and closing heavy window shutters, which participants refer to as 'getting the ship ready for the night' are described as activities that are lovingly carried out. Installing solar PV is not a one-off financial investment, but involves a laborious set of new routines in order to make the most of it. People also developed highly detailed investigations into drilling down into the precise workings of their appliances, in order to fully understand what their precise energy consumption is, as being part of a continuous process of reflections and having a deep connection with such issues. It is part of a life style.

Amongst solar PV householders there thus appears to be a willingness to change behavior and an inclination to do so – although less is known about the precise requirements to support householders in these efforts. Any technological support in this direction would need to tie in closely with existing practices and have the potential to become part of new routines.

As highlighted by Crabtree and Rodden [6], there is a fundamental difference between the home and the workplace: the home is not driven by productivity and efficiency, but is characterized by multiple objectives depending on the context and the residents. Domestic routines, which they describe as automatisms, allow residents to complete typical actions without thinking about them. Shove [27] argues that there is evidence that many such routines are never questioned, and that changing notions over comfort and cleanliness have driven up our energy consumption without us noticing this. A typical example is the perceived need for the daily shower, which was not a common practice some 40 years ago.

Demand-Side Management and Demand Shifting

Demand Side Management (DSM) is an umbrella term that groups together techniques to reduce or optimize the end-user's energy consumption in order to reduce the cost and the environmental impact. Palenski and Dietrich [23] present a taxonomy of these techniques, including *Demand Response* and *Demand Shifting* both of which address the issue that, because electricity is very costly to store, it is important to consume most of it when it is available. Demand Response is a mechanism to automatically adapt electric loads depending on the electricity tariff – encouraging users to use more power during cheaper times and avoiding high tariffs. Such tariffs are specifically put in place as an attempt to even out the load of the overall electricity grid, and to shed sharp peaks in consumption that require turning on additional high carbonate power plants such as coal. However, there has been a critique on this approach, as it designed to balance the grid load and to reduce the cost to the supplier, which is not always compatible with other objectives such as the environmental impact or the end-user benefits.

In a field study involving 10 households, Constanza and colleagues [4] explore a different approach using an agent-based system to help households shift laundry routines based on the electricity tariff. They deployed *"Agent B"*, a prototype system that shows which time slots will be cheaper and allows householders to book washing machine time slots. As this was a simulated system, participants received a small budget at the beginning which they could spend as they wished. They report that some participants used the tool as a new way to organize their laundry, integrating it with other resources drawn upon to manage the laundry (e.g., social relationships, activities, and the weather); but that others struggled to fit in the change with their more spontaneous practices. The study suggests increasing user interaction around automated systems to take more advantage of them.

Pierce and Paulos [24] argue for an approach that allows people to use energy differently rather than simply promoting "using less", including energy demand-shifting and selecting the "type of energy" that is used. "*Demand-shifting*" is a particular form of behavior change where energy consumption is shifted towards times of the day when local production is at its highest, thus using "green energy". They conducted a simulation study involving two households over two weeks and identified that people mentioned that they would be prepared to shift some behaviors (in particular doing the laundry) but that other practices were considered non-negotiable, in particular cooking [25].

Smart Home, Engagement and Interaction

Davidoff and colleagues illustrated the complex relationship between the resident and a smart home system through a list of requirements including the need to 'allow for the organic evolution of routines and plans and designing for breakdowns' [8]. In a smart home system, routines and plans need to exist, but have to be breakable and scalable to support residents. Current smart home approaches tend to propose routines that are too rigid. A home system should also understand the different changes, periodic or exceptional, and the multiple goals of the residents which go far beyond the house's walls. A study showed that what people consider as 'Smart' is not especially high technology but what fits in with routines and avoids unnecessary work [21]. Furthermore, it is not smart if people can do it better themselves [21].

Many Building Management Systems (BMS) have been developed with a focus on automation, severely curtailing the involvement of inhabitants in the control of their buildings. Yet several studies have pointed out that buildings designed to be carbon neutral are found not to be so in practice, and that the difference between the design intention and the actual performance is due to the behavior of occupants and the complexity of the interface to energy management systems [13, 28]. Usability studies of home thermostats found that homes with programmable thermostats consumed more energy than those relying on manual thermostats [22]: occupants found thermostats baffling to operate and many people were unable to fully exploit even the basic features of modern programmable thermostats. Furthermore, a recent study of the NEST automated thermostat showed that while residents initially were engaged in interacting with the new device, over time they settled into patterns that resulted in missed opportunities for energy savings [30].

In her review, Fischer [10] showed that energy feedback savings range from 5% to 15% of energy. She reported that households are keen to have information that is easy to understand – through labelling and explanations that are supported by graphic representations. Constanza et al designed 'FigureEnergy' to encourage users to engage with energy by labeling the energy consumption events [5] creating a view of the energy consumption 'per appliance'. The authors conclude with encouraging results through an in-the-wild trial in twelve households, engaging the users with their energy consumption and leading them to think more in terms of the activity rather than the appliance.

A question that remains is how to precisely interact with household members - which mechanisms to use in order to tie in closely with where the routine of the laundry is taking place and how people do their planning. In a study by Gleerup and colleagues [14], text messages and emails were sent to a large number of households across Denmark providing energy consumption feedback and resulted in 3% of energy savings. Alan and colleagues [1] studied human-agent interactions in the context of a home energy management system. They used text messages as communication between the user and the system as a complement to their web portal. They showed that users were happy with daily text messages and replied to the system.

User interaction can also be combined with automation at the time of use. In the Netherlands, Kobus and colleagues [18] deployed a 'Smart wash' in 24 households, employees of Enexis, with Enexis Energy Management System (EMS) and solar PV on their roofs. On the EMS display, householders were able to see the generation forecast and to set a deadline for their washing machine load to be done. Then, the washing machine started at the best solar generation period. The authors report that people tend to shift their washing to the peak solar generation period. They also noted that some household members were unable to become interested in the washing machine as a smart appliance with energy saving potential, as doing the washing was not part of their role in the home. Hence the social dynamics surrounding household routines and the division of labour within the home are issues that will impact on the success of new technological approaches to support the change of such routines.

A USER STUDY TO UNDERSTAND THE ROLE OF TECHNOLOGY AS A MEDIATOR BETWEEN LAUNDRY ROUTINES AND ENERGY DEMAND-SHIFTING BEHAVIOR

Digital technologies can potentially play a role in helping people become more effective "*demand shifters*" but the design of digital interventions is made difficult by our limited understanding of existing energy shifting behaviors, our limited understanding of the adjustability of domestic energy consumption, our limited understanding of the constraints that various life patterns impose on demand shifting behavior and the sheer breadth of available devices (smart meters, mobile phones, smart plugs, smart lighting etc.). In order to improve our understanding of the technical and social issues and – most importantly – their interrelationship, we conducted an in-the-wild user study with 18 households which focused on laundry as an energy consuming household activity. The user study sits within a wider program of research, involving some 75 households in Milton Keynes investigating issues around household electricity usage.

Why Focus on Laundry?

A typical modern washing machine uses a modest amount of energy and thus shifting laundry behaviors only promises small savings. However, prior studies show that people already adjust laundry behaviors "to catch the sun" [18, 25, 26]. Furthermore, most households (in the industrial world) have a washing machine, and doing laundry is an activity that is strongly influenced by social norms (about cleanliness) which can hardly be neglected. Doing laundry is strongly influenced by external temporal constraints (the need to have clean laundry ready for work or school), and it is (often) a collaborative activity that requires communication between family members. We thus see doing laundry as a prime subject for investigating technological support for domestic energy demand shifting.

Laundry routines are an important part of most households while energy use and climate change are global problems. The question thus arises, how can we design smart technologies that allow people to more effectively shift energy consuming activities and adjust people's routines?

Study Design

In order to gain an understanding of the interrelationship between social and technical factors we decided to explore a range of technology interventions - rather than focusing on evaluating one specific technology design. Specifically, we decided to explore four interventions along a temporal dimension:

1. The first intervention, which we refer to as *delayed feedback*, entails the use of email to inform members of a household how well their laundry activity aligned with energy generation *several hours after* they used the washing machine (typically at the end of the day).
2. The second intervention, which we refer to as *real-time feedback*, entails the use of SMS messages to inform members of the household how well their laundry activity aligned with energy generation *immediately after* they used the washing machine (typically within a minute after the washing machine turned itself off).
3. The third intervention, which we refer to as *proactive suggestion*, uses SMS messages to inform members of a household at the beginning of each day about the best time to do the laundry during that day – i.e. *several hours before* the use of the washing machine. “Best time” in this context refers to the start time that would maximize the consumption of self-generated energy (and thus minimize the energy export to the grid).
4. Finally, the fourth intervention, which we refer to as *contextual control*, entails the use of an interactive display attached to the washing machine to inform members of a household about the best time to do the laundry *and* to enable them to set the machine to *automatic start*, a new washing machine control mode we designed to start the machine automatically at the best time. As before, “best time” refers to the start time that would maximize the consumption of self-generated energy.

The first and second interventions rely on accurate analysis of energy consumption and generation during that day in order to compute shifting benefits. The third and fourth interventions rely on a predictive model of household-specific energy consumption, generation, import from grid, export to grid, local weather condition and washing machine use based on historical data collected over several months from each household.

The design space of these four interventions is shown in Figure 1. The horizontal axis indicates time, with events taking place before the use of the washing machine shown to the left and events taking place after the use of the washing machine to the right.

We conducted a study with 18 UK households (Table 1), over a period of eight months. We divided the 18 households into two groups with 6 and 12 participants respectively. We used the Group 1 as test group before launching Interventions 1 and 2 on Group 2. Due to time pressure, Intervention 3 was not done with Group 2 and

	People	Occupation Home / work balance	Average loads / week	W/M location
P1	2 adults	3 days working away, 2 days working from home	2.3	Kitchen
P2	2 adults, 3 children	Wife in on Mon, both out Tues to Friday	3.2	Util. room
P3	2 adults, 2 children	Wife at home, husband works mostly out	2.6	Util. room
P4	2 adults, 2 children	Both working out	3.8	Kitchen
P5	2 adults	Both working out	0.9	Kitchen
P6	2 adults, 1 adult Mon-Fri, 1 child sometimes	About 50% in / 50% out	5.7	Util. room
P7	2 adults, 3 children, nanny	Husband mostly away, wife works, nanny at home instead	1.9	Util. room
P8	2 adults, 1 child	Wife works at home, husband works	3.2	Util. room
P9	2 adults, 1 child	Wife works at home, husband works out	3.5	Kitchen
P10	2 adults	Mostly at home	3.9	Util. room
P11	2 adults, 1 child, 1 temporary guest	Work out	4.2	Util. room
P12	2 adults, 2 children	Mostly at home	1	Util. room
P13	2 adults, 2 children, 2 temporary guest	Wife works at home, husband works out	2.6	Util. room
P14	2 adults	Works from home, husband works out	2.3	Util. room
P15	2 adults, 2 children	Mostly at home	2.4	Kitchen
P16	2 adults, 1 child	Wife flexible shift and husband 3-shift	8.5	Util. room
P17	2 adults	Retired, lot of activities outside	2.4	Kitchen
P18	5 adults	All working out	1.8	Util. room

Table 1: Details of participating households

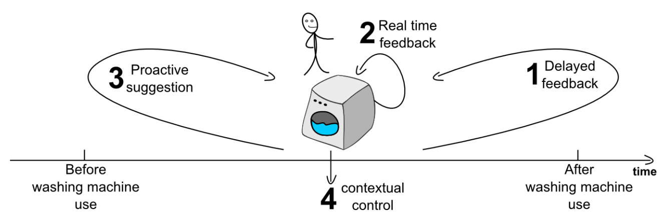

Figure 1. Interventions through the washing process

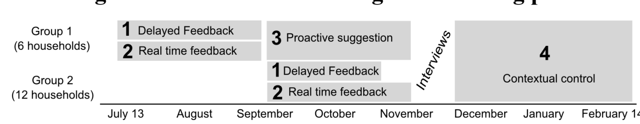

Figure 2. Schedule of intervention deployment

Intervention 4 was launched on both groups at the same time. Figure 2 shows the different stages of the deployment, divided in two groups of participants. In citations we use ‘W’ (woman) and ‘M’ (man) to indicate the gender of the household member.

Although all participants owned their own homes they had diverse demographic backgrounds (from childless mixed and single-sex couples to large families, one or both partners employed or one or both retired) and exhibited a diverse set of life patterns (some spending most of their time at home and others spending most of the day at work).

We collected data through interviews with family members that took place at home and a questionnaire. We also conducted focus groups with the participants during two sessions (half of participants each time) that took place at a communal place away from homes. During these sessions we asked them for their feedback about the interventions and reflections on their use within their domestic setting. Data about energy generation and consumption was collected several months before the study and throughout the study (solar generation, overall consumption and washing machine consumption).

Technology Set up

Each participating household was equipped with three smart meters to measure: (i) imported energy from the grid (the typical fiscal meter), (ii) generated energy from the solar panels and (iii) the exported energy to the grid. The smart meters recorded data every 3 minutes. Ten smart plugs were also deployed to monitor the energy consumption of individual appliances. Apart from tracking the washing machine, households were free to monitor whichever appliances they were interested in. Each household was also given a specially manufactured Indesit “smart” (ZigBee interface) washing machine which can be controlled from a distance and also provides status information.

The four interventions are based on the same general system that collects the data from the meters, smart plugs and washing machine and uploads data to a cloud server. The data are complemented by a generation and consumption prediction based on the cloud cover forecast and the generation and consumption of the last 20 days.

INTERVENTION 1: DELAYED FEEDBACK

Design

For the first intervention, we sent emails to the participants every three days with two sections in each email, as shown in Figure 3.The lower section showed graphs of historical energy generation over the last five days. Icons of washing machines indicated each load with its duration (length of the ribbon under the icon). This graph aimed to relate the local generation with the specific event of consumption, i.e. washing machine loads.

The upper section of the email displayed five battery icons representing the amount of energy predicted for each of the five following days. The prediction was based on the daily cloud cover forecast and was intended to inform the user about the potential of their energy generation for the coming days. Five days was chosen as the maximum semi-reliable forecast period for this part of the UK. Even though we included energy predictions, the emphasis of this

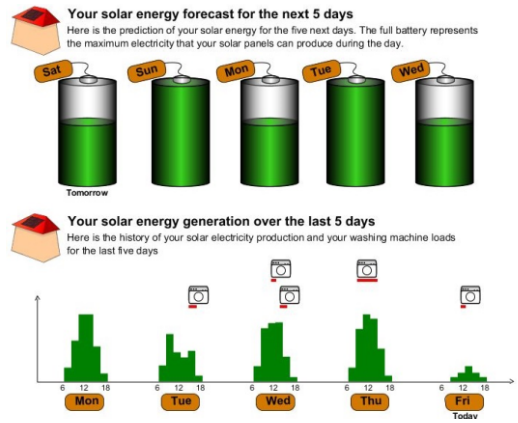

Figure 3. Intervention 1: Email with historical and forecast

'You ran your washing machine at 12:04 and 15:45 today (3.7% green). You could have achieved 43.6% by starting it at 10:34 and 13:52.'

'Congratulations! You ran your washing machine at 13:48 today (65% green). The expected maximum for today was 71%.'

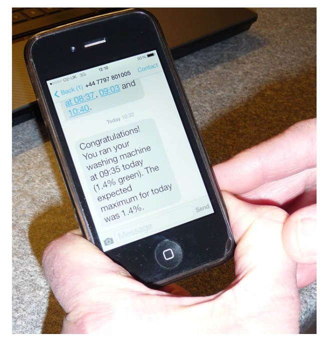

Figure 4. Intervention 2 – SMS Message examples

intervention, as highlighted to participants, was on showing historical data.

Findings

This intervention did not result in any feedback from the participants. The key reasons was that participants rarely checked email. Many had found that they either received too many emails and therefore ignored these while others checked their email too infrequently for the information to be relevant. The historical information seems to have been too far removed in time, or in place (with a number of households only receiving emails through their computer in a separate study upstairs) from the washing loads to have motivated any change in behavior or comments. Just one participant remarked that he was sorry the emails stopped, as he had found the predicted energy generation information useful for planning purposes.

INTERVENTION 2: REAL TIME FEEDBACK

Design

The second intervention involved SMS text messages to participants’ mobile phones. The users received a text message after each washing machine load. These text messages contained information about how much of the energy that was used for the washing had come from local generation (in percent), when would have been the best time to start the washing machine and how much local energy they could have used (in percent). Figure 4 shows some example messages.

The aim of this intervention was to increase energy awareness relating to local solar PV generation and the potential for local use by a specific appliance (termed "green consumption"). We wanted to understand how participants reacted to timely energy feedback by text messages and whether or not they made use of these texts.

We congratulated the user each time the actual "green consumption" was at least 90% of the best green consumption achievable. This measure allows the advice to be independent of seasonal variations: if the weather for the current day is bad, then the greenest consumption achievable is low and users can still be congratulated when they use a large part of this tiny solar PV generation. We fixed the threshold at 90% after trying several values over the first month. This value offers a balance of "congrats" messages and other messages.

These text messages were sent over five months (583 texts), initially to 6 households and later to all 18 households. Our aim was to send the text message as soon as the washing machine was finished so that the message was timely. However, it appears that, due to a technical limitation, we were getting the data about an hour late so the users often received the text about an hour after the end of the load.

We allowed and encouraged participants to reply to the messages, but only a small number chose to do this: we received a total of 5 text messages from 2 of the 18 participants (P2 and P11). Both indicated that participants believed there was an error in the text they had just received.

Findings

Most of the participants reported that the text messages were a good way to receive the information when compared with twice weekly email messages. However, for those who rarely received normal text messages, these washing machine messages were disturbing:

> P6-m: "you know, I don't get a huge amount of text messages so when I do get a text message I sort of look at it and sometimes it's only a message from you telling me my washing machine…"

Although we phrased the wording of the text messages as recommendations, we were expecting feedback from participants. In fact, some of them enjoyed receiving texts "coming from their washing machine" while others disliked it for two reasons: some participants did not like being told they had not achieved the best possible while others just resented being told what to do.

> P6-m: "it's only 49 percent and you could have achieved a hundred percent if you did this, arrh! You know, a little bit, you feel almost a little bit guilty! haha! I don't want to feel guilty you know"

> P14-w: "if you send me a text you should put your washing machine on now, I just get very... because I would be just, I think it would just irritate me, hmm other people might take it differently but …"

We also observed the reverse effect with some participants, where they appreciated the "Congratulations!" message.

Participants also noted the retrospective aspect of these text messages and the fact that they couldn't act on them as the event was in the past. The only kind of support that can help participants, such as P14-w, is a fully automated control. She reported being irritated by the text messages because she had already chosen to run the dishwasher (another high energy appliance) at the time suggested to run the washing machine so the message punished her for doing something unavoidable.

> P14-w: "hmm I didn't find the text messages particularly useful"

For other participants those text messages were a good reminder, but they found that it came too late to change anything.

> P6-m: "when you get the message afterwards it's too late you know you've missed your window."

This was also noted by P3-m who referred to our first intervention (by email). He highlighted the fact that we stopped sending these emails which he had found useful for planning. Without these emails he describes the text messages like getting a result for an exam that he did not study for. P3-m also compared the demand-shifting to *"shooting in the dark"*, explaining that they did not have the right type of support to help them achieve a high score:

> P3-m: "what I did find, there is feedback in the text message that "you ran your washing machine at this time" and "you were 42 percent green, the best time would have been... when you would have achieved..." But how would I have known that??"

For many participants, the interesting element of these text messages was the green percentage of the last load which revealed how much energy consumed by the washing machine had come from their solar panels. However, P10-w provided an interesting critique on the text message approach:

> P10-w "unless you're going to keep all these text message and analyze them, you are not going to get that information. Just saying 'your washing used 63 percent of solar', that's in itself is not really useful to us"

In this extract, P10-w explains that it is difficult to reflect on the text message with only the loads of the current day as insight. She notes that she felt she could not learn from the text messages. Although some participants reported that the real time feedback was useless when they were receiving the texts, many asked us to start sending them again when we stopped the study.

An interesting finding relates to the recipient of the SMS. At first, we asked each household to nominate one mobile phone number which was usually the person most concerned with energy use and who had initially signed up for the wider overall study. Later some of the participants asked us to change the number for some participants or send to multiple numbers. It emerged that the person in the household concerned with energy use was often not the person who was the main washing machine user. From the time we started our study, to the point where we were sending these messages, these washing machine users not initially concerned with energy use became more involved in the study and more generally in energy issues. For them, the washing machine was a concrete application connected to a routine they cared about. During our interviews we felt much more excitement from these participants than from the usual "energy leader" in the house and this was also something that emerged during focus group meetings.

INTERVENTION 3: PROACTIVE SUGGESTION

Design

For the third intervention we kept the text messages, but instead of informing users after the load, they received a text message in advance suggesting the best time to run a washing machine load. Figure 5 shows examples of the proactive text messages. The aim of this intervention was to help users plan ahead for the best period of solar generation for the current or the following day. Here we wanted to know how users perceived these suggestions and whether they were able to make use of them. Text messages were sent over two months to six participants (182 texts). For this intervention we asked participants to give us the times and days they wished to receive these text messages and we were surprised by the diversity of answers. Of the six participants, some of them asked for a text every day, some others wanted the text messages on very specific days, some wanted a message in the morning for the current day and other in the evening for the following day.

At the selected day and time for each of the participants, we sent a text message providing the best 2-hour period to run their washing machine. We also noted if the following day would be a better or worse period.

Findings

The participants were in agreement that the pro-active messages were more useful than the real time messages, although they noted that they did not always follow the suggestions.

Although only six participants received the proactive text messages, all the participants told us that such text messages would be better than the real time messages, in order to give them the time to plan and anticipate. For those who did receive the messages, they noted that even if they did not look at or follow the suggestions they felt a sense of appreciation that the information was there for them.

'If you want to run your washing machine today, then 13:15-15:15 should be the greenest time, but running it tomorrow between 10:45 and 12:45 would be better.'

'If you want to run yo washing machine today, th 12:30-14:30 should be t greenest time. It is a bett day than tomorrow.'

Figure 5. Intervention 3 – Proactive Text Message

Among those who received proactive messages, we noted two distinct groups. One group did not mind receiving a text every day early in the morning, because they did not a have specific washing day. The other group preferred receiving a text on specific days and would prefer a system that analyzed the pattern of their washes and that would send a text in the morning of the most probable washing days. For example, P8-m would like to receive a text on Wednesday, Friday and Saturday:

> P8-m: "of that day say around 9 o'clock, half eight in the morning, saying 'washing today at 4 o'clock or 2 o'clock would be a good idea, you would be using x amount', that would be really useful"

Participant P9-w made an interesting comment that she needs the text in the morning instead of the evening for the following day. This was in common with others who first chose to receive messages in the evening and changed their minds.

> P9-w: "because it's actually on the day itself because I always found there is a differentiation between sending it the day before thinking of that is a great time, I was outside so I didn't look, so I mean on the actual morning, like sort of pop up at 7 in the morning, we are mostly up and changed, ready for work or schools or whatever"

Although the proactive text messages seemed more useful for the participants, most of them noted that they would prefer a more automatic system that turns on the washing machine at the best time by itself.

> P2-m: "It would be good like at 7AM in the morning let's say, you got a message saying 'today we think the best time to start your washing machine is x'. Yeah that would be useful but I'd probably rather it was one of those to do it for me, you know? I really just wanna put the stuff in the washing machine and say I want clean clothes by 6 o'clock tonight, you do it yourself"

INTERVENTION 4: CONTEXTUAL CONTROL

Design

The last intervention involved an application on an electronic tablet that could control the washing machine. The tablet was fixed next to the washing machine (see Figure 6) and was meant to replace the washing machine's control panel. We designed an application with the minimum of controls. When the user switched on the washing machine the application woke up and displayed a time line of the day including the flags for "now" and "best". "Best" represents the best time to start the machine, depending on the selected load and the generation and consumption prediction. A slider allowed the user to define an "earliest" time to start and a "latest" time to finish the load. Then the user chose "Best start" and the washing machine would be started automatically at the best time. Otherwise the machine could be used normally by pushing the button labeled "Start now" which started the washing machine right away. At any time the user was able to ignore our application and use the washing machine as usual. Sunrise, sunset and cloud forecast were used to show the reasoning for the expected best time. Two battery icons displayed the estimated amount of energy coming from the grid and from the solar PV for the two given start times.

The application received fresh data every 30 minutes (overall energy generation and consumption, weather forecast) and updated the expected best time in respect of the "earliest" and "latest" constraints defined by the user. We deployed the electronic tablet with the application in seventeen households over three months (one resident declined to use it on grounds of having issues with the design of the washing machine itself). Through this intervention we aimed to observe how an assisted demand-shifting application was perceived by householders. Did they use the application? Did it fit with their daily routines?

Findings

Participants' expectations were much higher than what our application was really able to do. Furthermore, as soon as we set up the application in their house, participants came up with various suggestions to further tweak it. For example in the original set-up, when residents had selected a suitable best time, the washing machine was then delayed and started at the specific time. The first improvement that participants were interested in was to update the best time in case of weather change. They wanted to define an earlier time and a latest start time and say "Run at the best time in that window of time". We implemented and deployed this functionality a week after the study begun. The second suggested improvement was about the control during a washing machine load. "If the generation is suddenly not as great as it was supposed to be, pause several minutes and resume later." We did not implement this functionality because of the granularity of our weather forecast and because the energy balance: pausing the washing machine when it is heating the water results in losing energy.

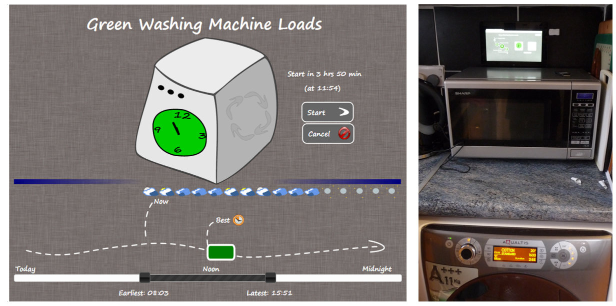

Figure 6. Intervention 4 – Washing machine control (left), Example installation in situ (right)

Overall, most of the participants were impressed and approved of the various possibilities the application allowed, including taking account of the selected program cycle to generate a suggestion. They found it easy to select the best time to start the load. In terms of display, some participants would have appreciated more details, which would have resulted in a more complicated display. For example, some wanted to understand how the decision for the best time had been made, perhaps with an indication of what the expected weather for that best time was compared to other times so they could judge for themselves which was better. They also wanted to answer the question: how much better this best time would be compared to running it now? They clearly wanted to evaluate their convenience against the benefits of shifting the load. This finding echoes existing research on intelligibility of context-aware application [19].

> P3-m: "So for example, close to the number 1, at 10:57 in the morning … But by knowing that we are going to run it at 62 percent green and that the 2nd option is only 61 percent green, then I can say I'll take the second because the difference is only 1 percent"

One major theme that emerged during our interventions was the interaction between appliances, which turned out to be more important than synchronizing consumption and generation. A common rule applied by all the participants was *"Do not run several heavy load appliances at the same time."* As soon as we started the last intervention with the washing machine application, we received informal feedback from the participants by email and during technical visits saying that they were not making use of the application in the way it was intended, because the suggested time was conflicting with other appliances.

> P2-m (by email) "I generally use delay start on the machine because the tablet generally suggests a start time which coincides with my heat pump and the hot water cycle!"

It is interesting to note that we received some similar feedback during the previous interventions, but it was much stronger and widespread with the washing machine control intervention. It seems that when participants received the information through text messages they were able to flexibly interpret the information and adapt it to their own setting whereas with the control of a single appliance they were not. In contrast, when the washing machine was not needed, participants reported using the suggested best time of the washing machine application to run another appliances such as the dishwasher or the dryer. Half of the participants described spontaneously what would be their ideal energy management system beyond the washing machine itself.

P14-w is at home most of the time and she already runs her washing machine at a very good time. She represents the "best users" who could only increase their self-consumption with an automatic system. She has in-depth knowledge of the details of the heating cycles of her appliances and wanted a fine-grained sync between the dishwasher and the washing machine. In fact, when the washing machine load visualization was showing a wash not so green, most of the time it was because the dishwasher was running during this best time. A close interaction between these two appliances would allow her to run them at the same time and pause one of them when the other is heating. Manually this is not really possible, as a normal user can only run them one at a time and they have no control over when each heating cycle begins. Similarly, P16-m said that he would prefer a system which automatically looks for the best time for the washing machine but also for other appliances such as the dryer and the dishwasher in a priority order:

> P16-m: "I would like all my free energy to dry my clothes and then if there's enough free energy left after that I think I'd quite like to maybe wash the dishes"

Beyond interference between appliances, participants highlighted the notion of priority. For example, P6-m would prefer to use his solar energy for his hot water some days when he is back from cycling (when he wants to shower) while the dishwasher and the washing machine would be a priority on some other days. P10-w reported planning to cook and like most of the participants she does not consider the oven as shiftable. She would like the system to work around this "fixed load". When participants describe their ideal system, they mix situations, lifestyle patterns, information they receive from multiple sources, shiftable and non-shiftable devices, interactive shifting (washing machine, dryer and dishwasher) and fully automatic shifting (hot water, heating system). A central message from participant interviews and focus groups is about being able to change the priority depending on the context.

IMPACT OF INTERVENTIONS

In this study we focused on interactions between the user and the system through a series of interventions. While we accumulated much detailed data it is difficult to make conclusions about the financial and environmental impact of these interventions. First, washing machines in general are not huge energy users, especially the A+++ energy rated washing machine we used for the study (1.82% of the overall consumption on average for our participants during the study). Secondly, most of our participants are already trying to shift their load manually, which makes the potential savings even smaller. Our best fit algorithm highlighted that in the ideal case, i.e. if participants had started all their washing loads at the optimum time, they would have saved an average of £0.50 per month (€0.65/$0.80). Finally, we conducted our study over eight months from July to February which implies seasonal variations. In fact, in the UK the length of day is less than 8 hours in winter and more than 16.5 hours in summer which made the solar generation of our participants 4.4 times less in winter than in summer. In that context, the part of energy coming from the solar PV that powered the washing machine decreased over the period of the study.

DISCUSSION

Through these different interventions, we observed some overarching themes and confirmed some previous work on both the content of the information provided as well as the method and timing of delivery.

Disseminating Information – Where and When

In contrast to email interventions that did not generate many specific comments or reactions, our text intervention supports the results of Alan and colleagues [1]. This medium seems to be a good interface between a "home system" and householders. However, the content of these texts has to be adapted to the user, following findings of previous studies [15, 29]. While real time feedback appears less useful for advanced users of solar energy, they can be used as a reminder to increase energy awareness.

Participants appreciated the proactive suggestions through text messages. However, the right time to send them is highly variable in day, time and frequency. These parameters should be customized and adapted by the user. While some participants suggested usage pattern (context) detection to send these texts at the best time and day, others appreciated the regularity of messages so they could rely on the information. This shows how people were already developing new routines with and around the new intervention, similarly to the results by Constanza et al. [4]. The way the information was presented across the four interventions brought up further interesting issues relating to time and place and decision making processes around household routines. For most people the emails did not work, as emails were not read very regularly, and often in a dedicated study which may have felt quite removed from where the laundry activity is taking place. In contrast, the text messages were more successful, as typically people carry their mobile phones with them, and would check for such messages regularly throughout the day. They also use them in all the different places where decisions around washing take place: from washing basket areas, bedroom floors to utility rooms and kitchens. The mobile phone as a device that is often carried with the person is therefore a better medium to carry the relevant information to the user in the right place and at the right time. There was also evidence that the tablets, positioned near washing machines in kitchens and utility rooms were becoming a focal point for communication and that people were making them part of their new routines. Some households had gone on to using the tablet to control their music, thus integrating the tablet as part of their in-home entertainment, and other households used the information from the tablets to make decisions on running different appliances, like the dishwasher, which were nearby. This issue of time and place is an important one to consider when deciding on ubicomp technologies for the home setting, with each form of communication having its own preferred location as discussed by Crabtree and colleagues [7].

High-level Information

The most useful information for the users was high-level information, for example best shifting time or percentage of green energy instead of raw energy consumption and generation. This follows Mennicken and Huang's definition of a "smart system" [21] that makes a task better or faster. In the context of local PV generation it refers to the ability to support three different behaviors: anticipating, reacting and acknowledging. Banerjee and colleagues [2] highlighted the need for householders living in an off-grid house to *anticipate* periods of solar generation. We observed the same behavior with our grid-tied houses. Proactive text messages that provided the best time to run appliances depending on the solar generation were the most appreciated by the participants. These alerts could also be used to *react*. However, participants expressed the need to know in real time which appliances they could use to adapt their consumption. Doing this manually by looking at PV generation and consumption graphs was time consuming. Participants noted that the automation provided by the tablet control allowed a precision they could not achieve manually and was a huge time saving. Some participants also used the information to *acknowledge* their own behavior – to see that they were doing rather well, or treated it as a competition for getting the highest percentage.

Widening engagement around energy

Over the study, the flexibility of our system – such as changing phone numbers or customizing days and times to receive texts – allowed us to adapt our intervention to each participant and to make it fit with their routine. Clearly participants wanted that sort of flexibility. However, more than highlighting flexibility, it is evidence that household members who were not interested in energy issues previously were becoming more engaged now that the technological interventions related to a routine they tended to handle (washing). In addition, in some households more people became involved in doing the laundry now that it involved use of a smart appliance. This is in contrast to the findings by Kobus [18] where the division of roles in households seemed to have been more fixed and overall leading to disengagement rather than engagement. However, most importantly the drawing in of more household members into discussions around energy points to this being about an activity, a practice or routine, that people clearly care about. Whilst the wider energy trial had introduced a range of apps and web portals with detailed graphics of energy consumption these had not been of interest to these participants. However, for them the issue of energy balancing became alive when it was tied to the activity of doing the laundry and when they were able to fit it in with nuanced and detailed decision making processes around the home.

Multiple Appliances and Future Work

The interference between appliances is a major barrier for energy demand shifting. Participants wanted the system to be aware of the different appliances in the house in order to suggest or to execute an appliance depending on the other appliance's plan. This emphasizes the difference between a fully aware system that includes the user in the loop and with a fully automated system. We discussed that the actual savings that can be achieved by shifting washing machine loads are minimal, but that there is potential of applying the approach to other devices. There seems to be widespread agreement that beside the washing machine, there are a number of other appliances that are likely to be shiftable, including dishwashers, dryers and heating devices [3, 9, 12] but also new devices such as Electric Vehicles [11]. Our future work will focus on demand shifting when scaling to multiple appliances.

CONCLUSION

In this paper we explored four technology interventions aimed at helping households shift laundry activities to maximize the use of locally generated "green" energy, namely delayed feedback, real-time feedback, proactive suggestions and contextual control. Results suggest that feedback, delayed and real-time, is not an effective way of supporting demand shifting behavior. In contrast, proactive suggestions seem to align very well with the normal planning behavior in households. Contextual control, a novel way of engaging users with energy issues right in front of the washing machine, seems to align best with the micro-planning and micro-scheduling activities that people use every day to organize their life. We see contextual control as a promising design paradigm for all domestic appliances, not just washing machines.

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