Cost, Context, or Convenience? Exploring the Social Acceptance of Demand Response in the United Kingdom

Highlights

- Domestic demand response (DR) incentivisation should focus on convenience over money
- Household practices and dynamics can determine DR's uptake and efficient use
- Appliance features and external factors, e.g. weather and space, affect adoption
- Agency, clarity and reliability of DR's control and feedback are crucial
- Demonstrated method of generating a dynamic real-time pricing tariff

Abstract

The energy sector, and buildings in particular, are one of the main contributors to climate change. Demand-Side Management (DSM) has the potential to realise energy savings on the demand as well as the supply side. However, the domestic sector still presents a major challenge due to its complex nature, one of which is the element of human interaction.

A series of case studies comparing different user interface designs were undertaken to investigate domestic Demand Response (DR) in relation to automated washing appliances and their effects on occupants. Focus groups were used to inform the study design and to cross-validate case study findings. The aim was to identify factors that may influence adoption and implementation of DR, in particular incentives and feedback methods.

The results highlighted the importance of the intrinsic features of the controlled appliances as well as the wider social and physical environments they were operated in. The dynamics within households with limited resources, such as time and space, meant that convenience was key regarding DR system adoption, whilst financial incentives were suitable for initial user attraction. Dynamic pricing, commonly featured in DSM systems, was also shown to stress household practices and to cause both, efficient and inefficient energy use, if coupled with

automation. Furthermore, the agency, clarity and reliability of control and feedback mechanisms were found to be crucial with regards to DR acceptance.

The study suggests that convenience, including ease of system operation and household practice integration, should be DR's primary guiding design principle.

Keywords

Demand Side Management; Home Automation; Behaviour; User Interface; User Experience; Real-Time Pricing

1 Introduction

The energy sector is one of the main contributors to climate change. Globally, in the EU and in the UK, the domestic energy sector accounts for between 30 and 40 % of final energy [1-3]. A shift to Renewable Energy Sources (RES) is taking place [1]; however, due to the volatility of their availability, their full potential is not being exploited. This is exacerbated by the fact that price variations resulting from supply and demand mismatches are not being passed on to energy end-users. Hence, energy providers have to compensate for peaks in demand by providing emergency generation capacities. In the UK, power stations are on average 40 % efficient in transforming primary energy into electricity, whilst emergency capacities are only 34 % efficient [3]. This creates additional variations in the wholesale market prices, which are particularly noticeable during periods of peak demand. Yet, weekday and seasonal variations in power consumption, see Figure 1 and Figure 2, are predictable and therefore do not affect wholesale prices. Calculations made with data obtained from National Grid's [4] and Exelon's [5] websites revealed that the daily electrical power consumption within a year varied by ± 36 %. In contrast, the wholesale electricity price showed increases of up to 288 % compared to the daily average. The same principles apply to over-generation, which can result in negative wholesale market prices and lead to the curtailment of RES [6].

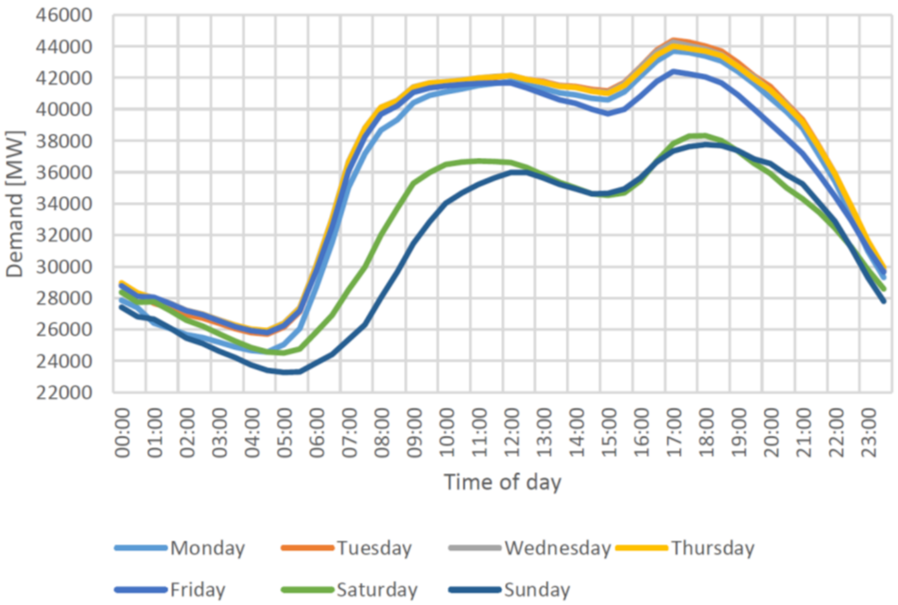

FIGURE 1: MEAN HALF-HOURLY ELECTRICITY DEMAND PER WEEKDAY OVER ONE YEAR[4]

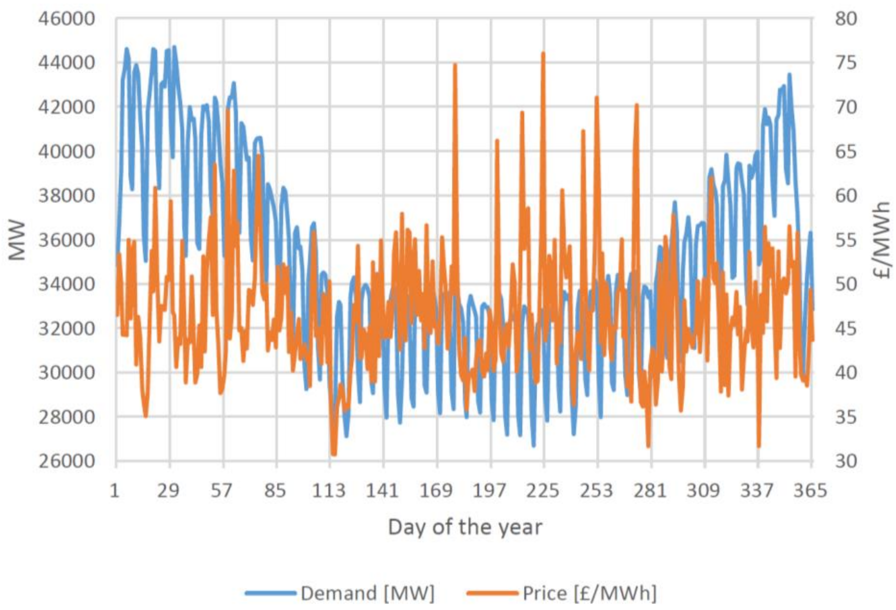

FIGURE 2: AVERAGE DAILY ELECTRICITY DEMAND AND PRICE FOR THE UK [4, 5]

Demand-Side Management (DSM) is one method that can alleviate the imbalance by using incentives to dis- or en-courage electricity consumption accordingly. Depending on the platform, DSM can be used for both automated Demand Response (DR) and incentivising behavioural energy saving measures. For example, a time dependent electricity tariff based platform could provide the signals required to automate machine operation, whilst financially enticing end-users to reduce their total energy consumption. DSM can therefore lead to savings on the supply and demand side.

To enable DSM, the necessary infrastructure is currently being rolled out worldwide [7], which comes in the form of smart meters coupled with in-home displays. These provide higher resolution energy data to the suppliers for billing purposes, whilst offering more in-depth information to end-users. The European Commission estimates that close to 200 million electricity measuring smart meters will be deployed across the European Union by 2020, representing approximately 72 % of all European consumers [8]. In parallel, smart home technologies are also becoming more pervasive, with many common household appliances receiving internet connectivity features and the ability for remote control; though the focus is often split between energy and other features, such as comfort, convenience and security [9]. This suggests that the enabling factors for DSM, and particularly DR, are largely in place.

However, there has been very little systematic investigation of how end-users deal with and adapt to an applied system. Studies have shown mixed results with regards to theoretical user acceptance. Some have suggested that automated control is preferred [10] [11], whilst others highlighted concerns about loss of control, the technical reliability and privacy [12] [13]. Studies also noted that users' implicit attitudes and motivations correlated with their trust in automation and their willingness to share energy data [14, 15]. From a practical perspective, it was shown that DR can lead to load shifting, cost savings and behavioural changes [16] [17] [18]. However, these studies generally focused on the technical feasibility rather than on the understanding of why and how users may engage with DR. In fact, users are often treated as passive variables in DR systems, despite being the ultimate users of the energy [19, 20]. In the context of comparable automated control systems, it was shown that perceived levels of control need to be maintained to facilitate user acceptance [21] and that poor user interface design can lead to misuse, which can cause energy inefficiencies [22]. Attempts have been made to incorporate these aspects into DR user interfaces [23, 24], however, they have not been validated by real users.

This study was designed to investigate the impacts of an applied domestic DR system on the users in a real-life setting, including a dynamic real-time pricing (RTP) electricity tariff and a range of user interfaces. Particular attention was given to factors that might affect the acceptance, adoption and implementation of DR, including incentives and feedback methods. The study revealed numerous interlinked and complex relations between the users, the appliances, the physical and social context they are operated in, and the ultimate impact a domestic DR system can have on energy efficiency and the social fabric within a household.

2 METHOD

A mixed method approach was used to evaluate perceptions and reactions to DR. Initially, focus groups including a wide range of society, as discussed in section 2.1, were conducted to investigate stated preferences with respect to DR. The results were then fed into the design of the case studies, outlined in sections 2.2 to 2.6, whose purpose was the assessment of DR receptiveness on a practical level using real-life households. After outlining the results from the focus groups and case studies separately, the discussion interlinks the common themes and seeks to outline corroborating evidence.

2.1 FOCUS GROUPS

The focus group work, as previously reported [25], consisted of four three-hour events, each including 18 participants that were further sub-divided into three groups, giving 72 participants and 12 focus groups in total. Each event took place in a different location, with samples representative of local demographic profiles in terms of gender, age and ethnicity.

The four locations were selected according to urbanicity and experience of community low-carbon energy schemes, such as domestic photovoltaic (PV), community-owned wind turbines and their associated feedback displays. The aim was to elicit a broad range of opinions across the topics examined. Two of the locations were rural, one with and one without experience of a community energy scheme and two were urban, with and without experience of a community energy scheme.

In order to probe participants' reactions to technologies they might be unfamiliar with, they were provided with a 15 minute presentation on the wider socio-political context of DR. Furthermore, three short film narratives [26] were shown, which presented accounts of households and their experience of a selection of DR technologies. In order to avoid biasing responses, a 'contravision' [27] technique was used in which each film narrative was told in 'light' and 'dark' versions. The light versions presented a positive account of user-technology interactions, the dark versions a negative one. The intention of the information presented was to both, inform participants and prompt them to consider the proposed technologies in the context of their own lives.

The results of the focus groups were subjected to a thematic analysis using Nvivo software [28]. Furthermore, the analysis was conducted using a practice theory lens, i.e. practices were treated as a combination of their four primary components: “materials and infrastructures”, “rules and knowledge”, “embodied skills” and “engagements and meanings” [29].

2.2 Households: Occupants and Appliances

In line with the results from the focus groups, see section 3.3, the aim was to automate washing appliances, as they are widely and frequently used appliances, with a considerable impact on domestic electricity consumption whilst not requiring the occupants’ attention during operation. For the case studies, three houses with long term occupants were chosen from a convenience sample, which are part of the University of Nottingham’s ‘Creative Energy Homes’ project [30]. House A was occupied by one male and two female students aged between 28 and 38. It was equipped with a washing machine and a dishwasher. The house also had other unrelated monitoring and control equipment, which meant that the occupants had some previous experience with building automation and feedback systems. House B was occupied by a married couple aged 23 and 30, and was equipped with a washer-dryer. House C was occupied by a family with the parents aged 36 and 37, and the child aged 5. The house also had a washer-dryer. It is worth noting that all houses had microgeneration systems and that each household had at least one occupant directly involved in sustainable research. To limit potential bias, a researcher without a personal connection to the occupants carried out the data gathering.

2.3 Dynamic Real-Time Pricing Scheme

At the core of this study was a purpose built dynamic RTP scheme, which was developed to pass on the energy saving potential on the supply side to the end-user. As described in the introduction, the inability to control electricity demand creates the need for peak matching power plants, which are less efficient [3]. Hence, a RTP strategy was designed with the aim to smooth electricity demand by incentivising electricity usage during low demand times, whilst discouraging it during high demand times.

Due to unavailable live data, National Grid’s [4] electricity demand and Exelon’s [5] wholesale prices were used as the basis for this realistic dynamic RTP scheme. To eliminate the seasonal variations in the electricity demand, as shown in Figure 2, the daily average was used as a reference. The demand data was then classified into low, average and high demand periods, using an arbitrarily chosen ±10 % threshold, which notably resulted in average demand periods during the day.

The historical cost was calculated for each given half hour period based on the System Sell Prices or System Buy Prices according to whether there was a surplus or shortage of electricity at that point in time. With reference to the historical energy cost and the combined energy consumed in each of the three periods per day, new prices were calculated for each half hour low, average and high demand periods, respectively. The calculation of the new prices ensured that, if those prices were applied to the original demand data, the original revenue per day would be achieved.

The developed dynamic prices were also aligned with the weekdays of the study periods, as Figure 1 pointed out that electricity demand varies throughout the week. An example of a day's classified demand in relation to its designed prices is shown in Figure 3.

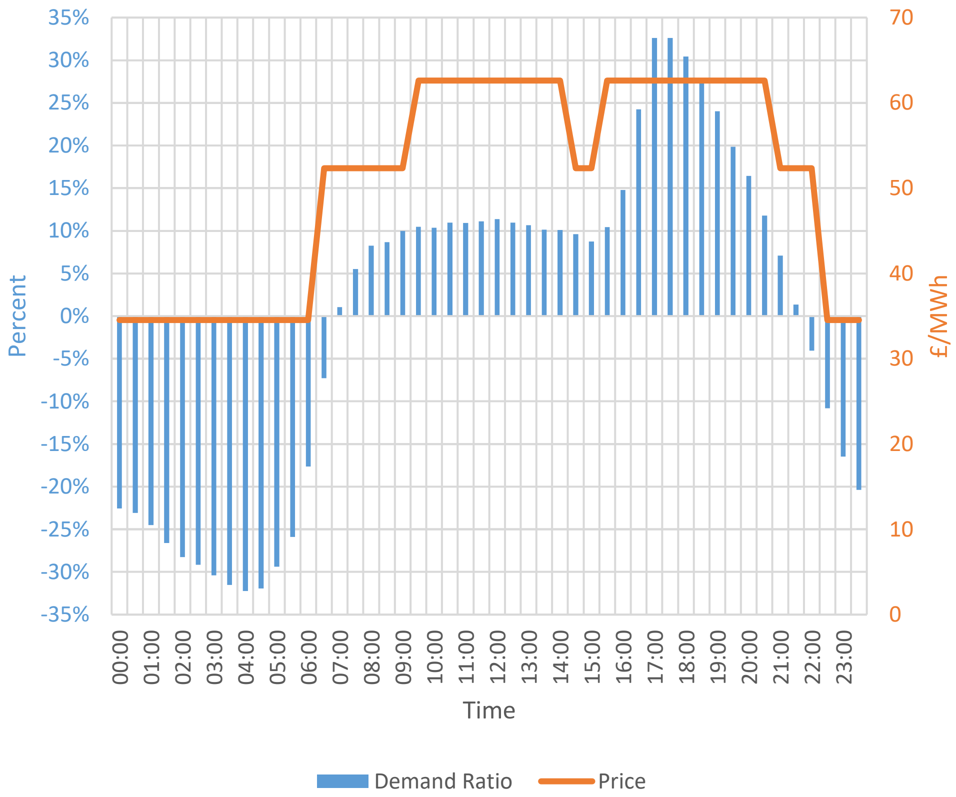

FIGURE 3: A DAY'S DYNAMIC RTP SCHEME DEDUCED FROM ITS DEMAND RATIO

2.4 Appliance Automation

As stated in section 2.2, washing appliances were selected for the DR automation. In order to interface each house's washing appliances to the developed pricing scheme, they were connected to wireless Enocean plug sockets, which in turn were managed by a Can2Go controller. Each controller had a web interface, which allowed the participants to interact with the system, see section 2.5. The controllers were programmed to switch the sockets on or off dependent on the given simulated price period and the price the occupants were willing to operate the appliance on.

For an appliance to start, the occupants had to initiate a program first. On detection of power consumption, the wireless socket opened the relay and waited for instructions from the controller. As this effectively meant that the appliances experienced a power cut, it was verified beforehand that each house's washing appliances would continue an interrupted program when power was returned. To ensure that subsequent appliance cycles could be distinguished and to prevent mid-cycle interruptions, a minimum time gap of ten minutes without any power consumption was used as an identifier of new cycle initiations.

Furthermore, a 'stochastic element' was included in the low demand price periods, which randomised the start of a planned program. Its aim was to emulate a staggered control approach, which would be required if large numbers of appliances were to be automated. Moreover, an algorithm was added to only start a program during a low demand price period, if it was able to finish before the end of that price zone. However, it is noteworthy that the control algorithms treated different days as different entities, meaning that the price zones before midnight were not linked with those after midnight.

2.5 User Interface

To simplify the information presented via the user interfaces, as requested by the focus group participants, section 3.2, the various price periods developed in section 2.3 were shown in colours rather than values. Hence, the low demand periods with the cheaper prices were presented in green, the average periods in yellow and the high periods in red.

Furthermore, four RTP electricity tariffs were created to allow users to select their preferred price periods: 'Green (£)', 'Orange (££)', 'Yellow (£££)' and 'Red (££££)'. The 'Green (£)' tariff only let the appliances run during green price periods, the 'Orange (££)' during green and yellow periods, and the 'Yellow (£££)' only during yellow periods. The 'Red (££££)' tariff allowed the occupants to use the automated appliances at any time. The occupants were able to set a separate tariff for each of their appliances and change them at any point during the study. The participants were made aware that the tariffs were purely fictional, and that no financial incentives were provided as part of this study.

In addition, three different user interfaces were tested, which offered various degrees of control and feedback to the occupants. The first, most basic interface, called 'website only', provided the occupants with the household appliance specific website, shown in Figure 4. Thus, with a device of their choice, they could set tariffs for each of their appliances and visualise the price periods. This interface was always available, including when other interfaces were tested. The second interface, called 'tablet', consisted of a tablet computer, which was connected to the mentioned website and setup next to each of the appliances. The third interface, called 'override switch', was a two-sided wireless Enocean pushbutton switch, which was installed on the household's appliances. Pressing its 'off' side was programmed to turn the DR automation off for one appliance cycle, thus overruling any previously chosen tariff and starting an initiated appliance immediately. Pressing the 'on' side was programmed to turn the DR automation back on, which was also done automatically ten minutes after the appliance's program had finished. Both, the 'tablet' and the 'override switch' were intended to simulate appliance integrated features.

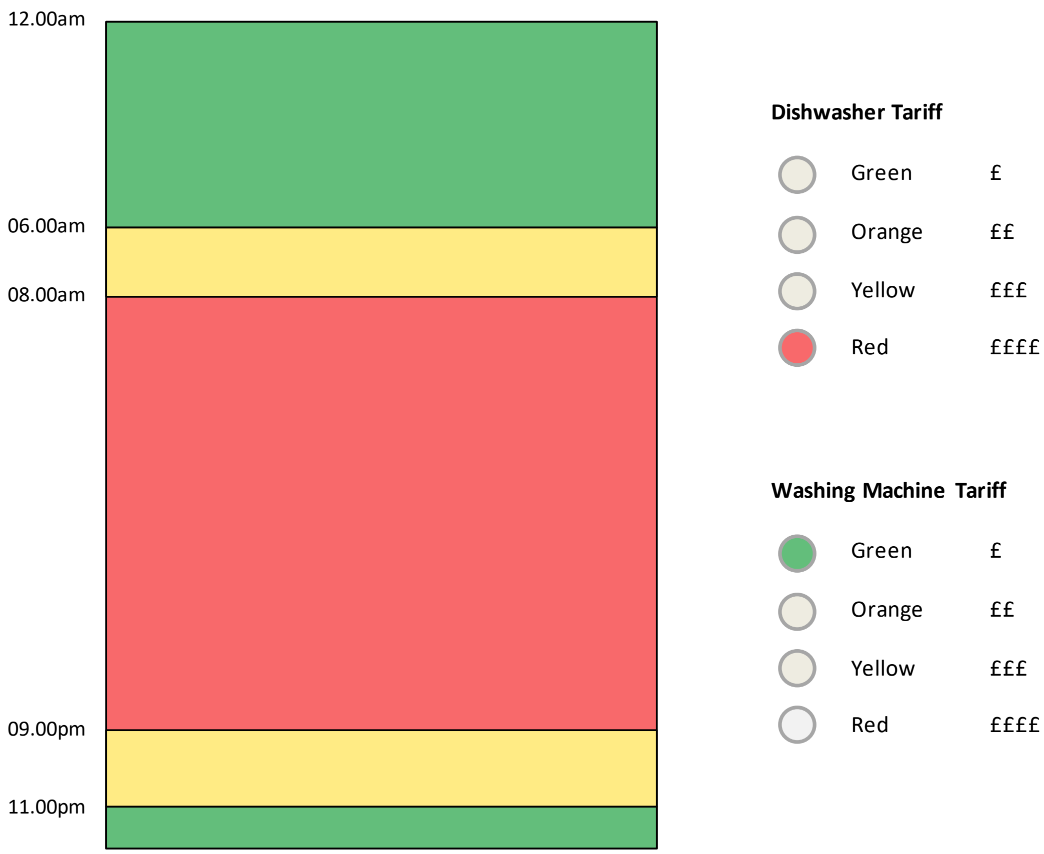

FIGURE 4: WEBSITE INTERFACE WITH TIMES OF LOW, AVERAGE AND HIGH PRICES AND SELECTION MECHANISM PER APPLIANCE

In each of the three houses, two types of interfaces were tested for several weeks. The durations of the resulting six case studies are presented in Table 1 along with each household's tested appliances.

House	Appliance(s)	Interface	Study Period

A	Washing machine & Dishwasher	Website only	24th September	–	21st October
		Tablet	06th November	–	03rd December
B	Washer-dryer	Tablet	16th October	–	12th November
		Override Switch	15th November	–	30th November
C	Washer-dryer	Website only	25th October	–	15th November
		Override Switch	16th November	–	03rd December

TABLE 1: DETAILS OF THE CASE STUDIES

2.6 CASE STUDY DATA COLLECTION

Data was collected by two means, the controllers and semi-structured interviews. The controllers recorded the occupants' interactions with the interfaces and the appliances. Every tariff change and every push of the override switch were logged. Also, the power consumption of each appliance was recorded with a resolution of up to 20 s, which allowed assumptions to be made on the time of initiation, start, length and finish of a program.

The semi-structured interviews were designed to evaluate the impact the DR system has on the occupants, including any potential behavioural changes and preferences with regards to incentives, interfaces and the system in general. Each adult occupant was interviewed before the start of the study, based on questions on their existing behaviour, perceptions, skills and interests in relation to DR, see Appendix A. They were also shown a prototype of the user interface and were asked to trial setting different tariffs to familiarise themselves with the system. However, they were not encouraged to choose a specific tariff for the duration of the case studies.
After each of the case studies, they were asked questions based around their general experience of the system, behavioural changes, expectations, incentives and willingness to share energy data, see Appendix B. The participants were then invited to provide suggestions on how the system could be improved.

3 FOCUS GROUP RESULTS

The focus group results that influenced the case study design and overlapped with the case study results are outlined here; for full results see [25].

3.1 ENERGY USE IN THE HOME

Energy consumption practices in the home develop dynamically through intra-household interactions and negotiations. Established practices can then become habitual, which is to say determined more by rote behaviour than conscious decision making. However, the introduction of microgeneration can initiate the radical reshaping of practices, as both energy production and consumption are redefined. Data also indicated that behaviours and values are co-constructive.

A further salient observation across features within the focus groups was the importance of recognising the multiple actors within a shared home, and the potentially complex power relationships that this creates in regard of specific practices and the control of them. In the case of cooking for example, one adult may do the food shopping, one may do the cooking itself, another may pay the electricity bill and it may be a child who effectively determines the time at which it happens. No one individual determines the practice. Such dynamics can make planning more difficult and calls for devices that can be used flexibly in response to the diverse, possibly competing, demands of different household users. Furthermore, whilst participants identified cost as a major factor in evaluating new energy technologies, their accounts of energy use in practice often highlighted non-monetary concerns as critical, such as convenience.

3.2 Knowledge and Visibility of Energy

For some participants, energy was and should remain invisible. Their awareness was largely limited to the activities it enabled; and they showed a lack of understand of how pricing worked or what the energy usage of different appliances was or might be. They argued that life was difficult enough without the added complication of having to include energy in their decision-making. Energy was just considered one of multiple contingencies of daily life, i.e. work, family and self. However, simultaneously, there was a strong desire to understand their energy consumption better, with many expressing discontent about the format of their energy bills. This appeared to be driven by two factors: awareness of the environmental pejorative to reduce energy demand and a widespread distrust of energy suppliers, which led to concern that participants were not getting the best deal. The result is a rather paradoxical wish to understand energy use better without having to expend much thought on it.

Technologies that might alleviate this tension were viewed favourably, with many expressing interest in devices that provided simple feedback about the amount of energy being consumed. The metric of kWh was highlighted as being difficult to interpret. Instead, the idea of presenting information simply and intuitively was welcomed, with suggestions to use coloured light to represent current electricity prices. However, those who already had in-home displays commonly reported that their engagement with them only lasted days or weeks, after which they were largely forgotten about. One technology that was far more successful at achieving ongoing engagement with energy, and affected actual changes in practice, was micro- or community-generation. For example, several participants with solar PV reported shifting practices, even 'point-of-use' activities such as vacuum cleaning, to periods when the sun was shining. Here, it was evident that the ready association of the solar panels with specific activities led these to acquire new associations and meaning for the participants. Engagement with displays, on the other hand, were hampered by a deficit of agency, that is to say, a means of actually acting on the information.

3.3 Time Shifting

Participants' openness to time shifting practices was determined by two factors in particular. The first concerned whether the user's participation in the practice was necessarily simultaneous with the energy consumption and the second concerned the meanings participants attached to a particular practice. The notion of time shifting point-of-use practices, such as showering and watching TV, in which participation and consumption are tied together, was viewed unfavourably due to the requirement for the user to rearrange their actions at the behest of the system. By contrast, responses to shifting practices in which energy use and participant involvement are asynchronous, as is the case with white goods, were largely favourable. For example, an individual could load a washing machine and let the system determine when it ran. As long as this occurred within a suitable time window that the user could specify, e.g. between 0:00 - 7:00, then their involvement in the practice could remain unaltered. The placement of this window of use was highly specific: for some participants, overnight running was impossible due to the potential for noise disturbing neighbours, for another the requirement was to have a 60 minute delay so that she could fall asleep before it started.

The second factor concerned the meanings participants attached to a particular practice. These meanings moderated responses to time shifting. For example, for many, a morning shower signified gaining alertness for the day ahead. Accordingly, the idea of moving the shower to elsewhere in the day made little sense. The situation might be reversed for a bath that symbolised relaxation and so was seen as suited to an evening time point. A second example was that of electric vehicles (EV) as a battery store. Whilst using the car batteries as a store and source for their own micro-generated energy was welcomed, participants were noticeably more wary of the idea of having an EV that was utilised in a distributed storage scheme by the power grid. It was hypothesized that a common meaning attached to car ownership, namely independence, was conflicted by such a scheme. Similarly, the meaning of energy ownership was questioned in relation to DSM. Participants were wary that energy usage monitoring, time dependent pricing and automated appliances could lead to a loss of autonomy over the ordering of domestic life; and that ultimately, ownership of energy could translate into ownership of the household.

4 Case Study Results

The data collected via the controllers is presented by house and by interface in Figure 5 to Figure 10, with an approximate precision of five minutes. Remarks to clarify relevant information were put underneath each of those figures. Detailed statistical analysis on the performance of the system and the frequency of its use can be found in [31].

4.1 House A

4.1.1 Pre-Case Study Feedback

The pre-study interviews revealed that one occupant had moved in shortly before the start of the study and therefore had little experience with the appliances. In contrast, the two established occupants had a washing up routine that rarely involved the dishwasher, which was used approximately one or two evenings a month. One participant was unintentionally put in charge of it and predominately used two programs. The washing machine on the other hand, was used once to twice a week per person. There was no set washing rota, it was only decided by availability. The time of use varied with each occupant. One mainly used it in the mornings and sometimes afternoons, one used it predominantly on weekends, and one usually in the evenings. Two occupants preferred to get a full load before starting the washing machine and usually set it on the same programs. The other occupant used it when required and at varied settings.

With regards to whether cost or environment was being considered whilst using the appliances, one occupant replied "in my daily life I always try to reduce my consumption of material or electricity". Another occupant stated that they worried more about the energy bills than the environment, but suggested that "if you save energy a bit, you sort of look after the environment anyway". The third occupant mentioned not being particularly concerned with cost or environment when using the washing machine. However, they pointed out that shared usage of constantly running appliances, like the fridge for example, was more economical and that the fear of electrical fires was a motivational factor for switching appliances off. Furthermore, all of the occupants thought that they currently had insufficient feedback regarding price and environmental impact of energy to be able to make informed decisions. In addition, they felt that researching provider specific information would be too time consuming and hence preferred to reduce their energy consumption instead.

The historic monitoring and control equipment installed in this house, mentioned in section 2.2, was able to reflect energy consumption, however, the occupants pointed out that they did not use this function due to that system's slow response rate. With regards to the prospects of using the proposed system, all of the occupants felt that the website interface would be easy to use. However, one occupant believed that people who are not computer savvy might have problems, or would need extra time to get used to it. After a demonstration of the system, one occupant thought that the appliance's "reaction time [was] a little bit long". Furthermore, concerns were raised regarding the noise of the house's rainwater pump, as that could potentially affect whether they would use the proposed system for night-time operation of the washing machine.

All of the occupants could see themselves using a similar load shifting system on a regular basis, mainly for the financial incentive. One occupant was also motivated by being part of a larger energy saving movement. The notion of being able to control appliances remotely was appealing, too. The occupants suggested that a developed version of the proposed system should present the financial savings in real time or overlay them with energy consumption data of previous months. One occupant proposed that the monitored data could be used to provide detailed energy saving advice.

4.1.2 Website Only – Case Study

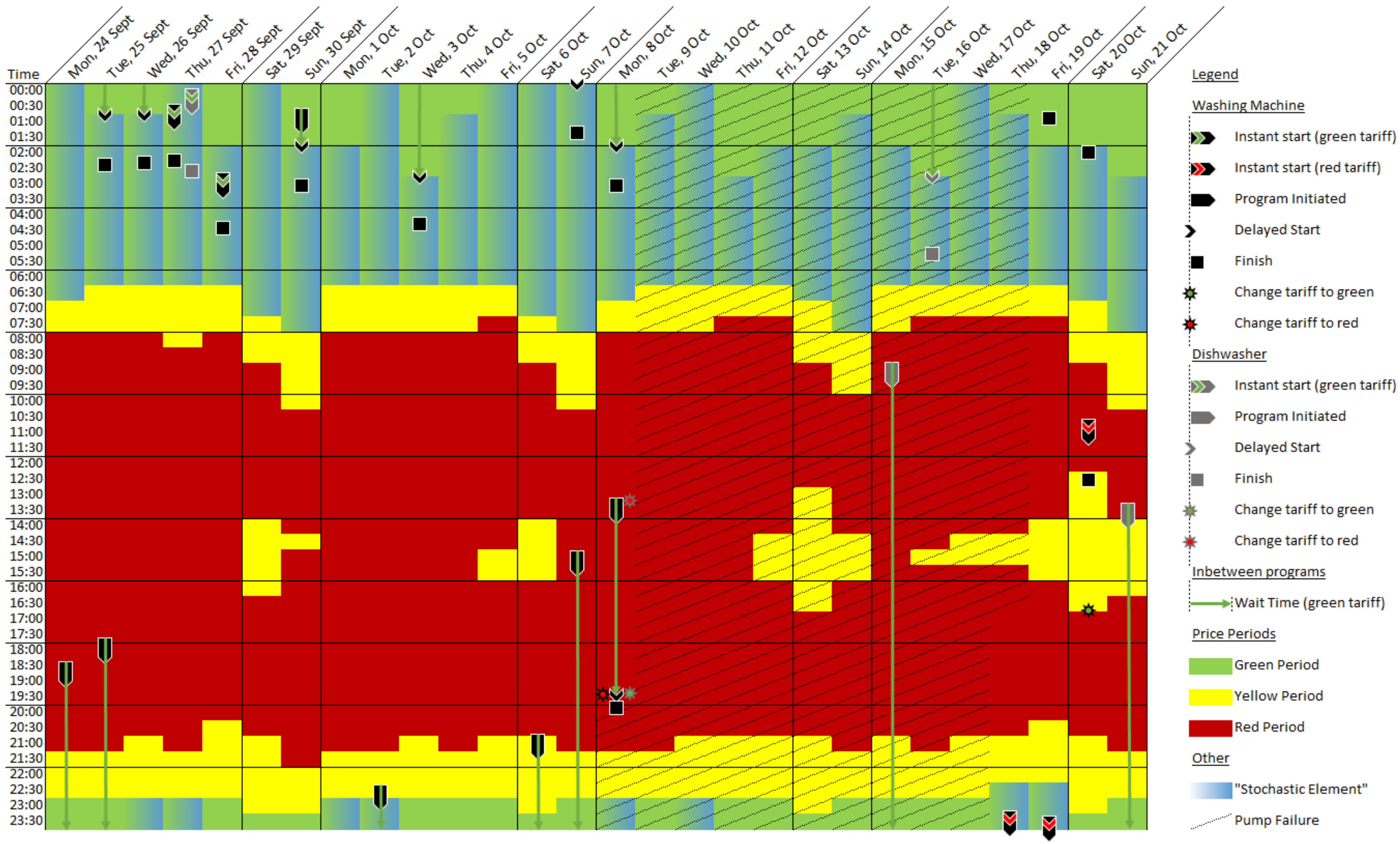

Figure 5: House A – Website Only

Remarks: On 8th October the initially noisy rainwater pump failed, which stopped the running program of the washing machine and inhibited any subsequent operation until 18th October. The pump failure had no effect on the operation of the dishwasher.

The occupants' overall impressions of the system after the 'website only' case study were positive. However, two occupants felt that they might need more time to adjust themselves to it. None of the occupants changed their preferred washing programs and there was no change in the way the dishwasher was used. Some occupants especially liked the fact that the machines could be operated in the same way as usual. However, one occupant thought that it was inconvenient that the washing machine only started after midnight, as that effectively meant that they could not take the load out until the next morning. They were also worried that wet clothes left in the washing machine for several hours might start to smell, especially in the summer. Usually, they would rinse and spin the load again if it stayed more than three hours in the washing machine.

The occupants also pointed out that only one person could use the washing machine in a day, if they wanted to use the green tariff. The added waiting time made sharing the machine a bit annoying for some. However, one occupant highlighted that previously there have been occasions where washed clothes were forgotten in the machine for up to one whole day and that "in this kind of situation you can actually adopt the habit to check the washing machine in the morning and you don't forget". Another occupant added that this ultimately resulted in them taking turns with using the washing machine and doing regular washes to avoid "wasting a night". The occupants also highlighted that if certain items needed washing for the next day, it was very difficult to dry them in time. As part of the wider context, the noisy rainwater pump, which was below one occupant's room, was mentioned as an issue. Its failure, reported in Figure 5, made them realise "how important this machine was, really".

All of the occupants said that they had moments when they wanted to change the tariff from green to red. Two occupants wanted to reduce the added waiting time, but resisted due to internal motivations and the system's reminder that the current tariff was cheaper. The third occupant wanted to use available sunshine to dry their clothes, but did not know how to change the tariff.

All of the occupants were interested in the savings made and could see themselves using this kind of system on a long-term basis. Theoretically, they would also allow the collected data to be available to third parties, such as private companies or public institutions. Their motivations for using the system did not change in relation to prior to the study. However, one occupant highlighted that the savings needed to be substantial in order to continue using it. Several pound sterling (£) per months were expected. The other two occupants were content with any kind of financial gain, as they saw the change in lifestyle as "simple". However, when prompted, one occupant estimated financial savings of 10 % and the other of 50 % to be a sufficient incentive. One occupant suggested that this type of system would be supportive during weekdays and inhibitive during weekends, due to the available times on green price periods for household chores. Furthermore, it was suggested that future systems could consider weather forecast data to allow for optimal drying conditions.

4.1.3 Tablet – Case Study

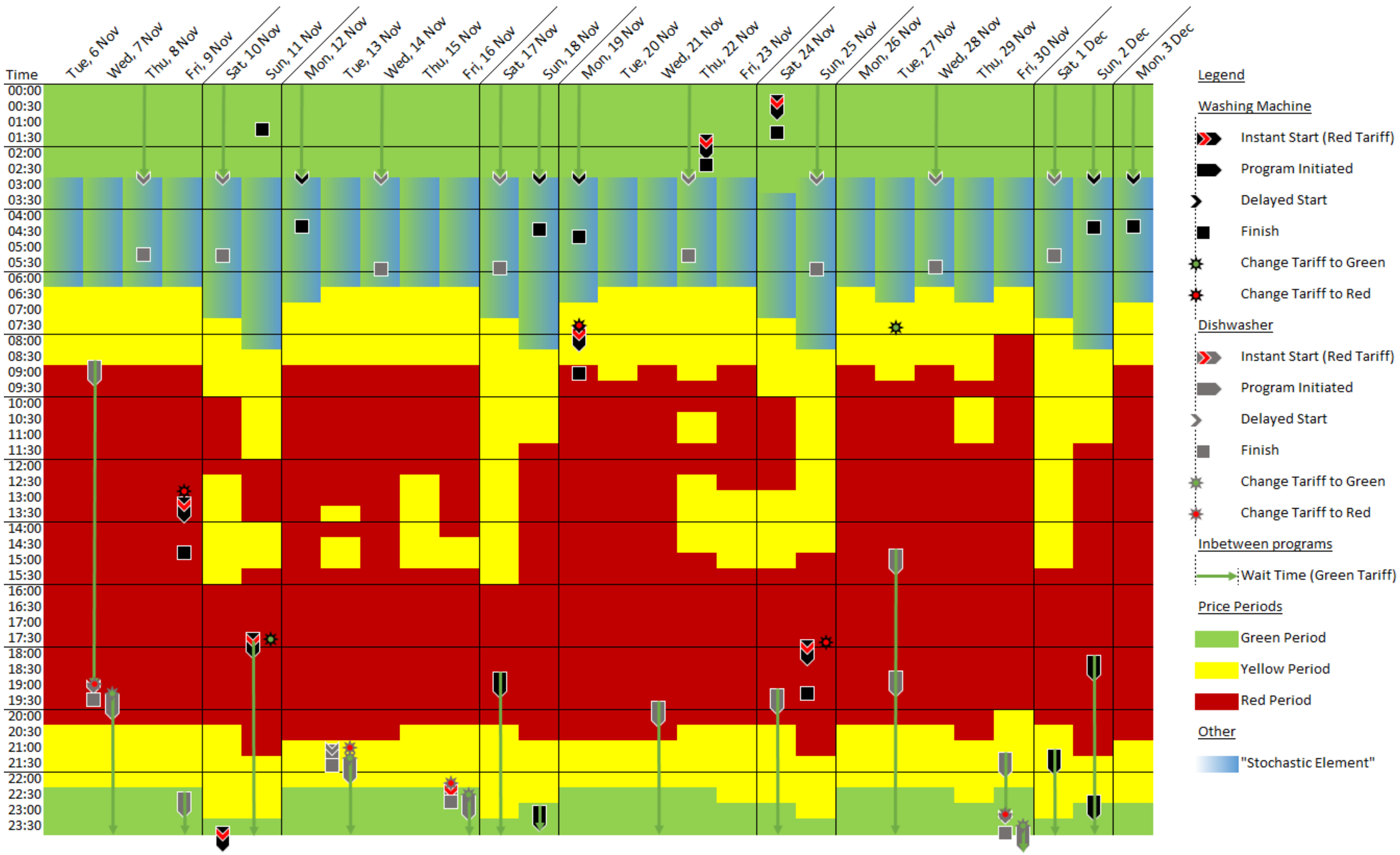

Figure 6: House A – Tablet

Remarks: One occupant was absent for the first fourteen days and another for the last fourteen. Due to this, the latter occupant was post-interviewed two month after the case study had finished.

The occupants stated that the dishwasher was used more frequently during the ‘tablet’ case study, but they suggested that the responsibilities over it had not changed. The occupant, who was predominantly in charge, pointed out that the pre-wash program, which was necessary to clean the dishes fully, could not be selected in conjunction with the main program. They also added that during the ‘website only’ case study they omitted this program, as they would have had to go to their room to change tariffs. However, with the tablet, they decided to use the red tariff for the pre-wash program and then switch to the green tariff for the main cleaning program. Another occupant suggested that a dishwasher was more compatible with a DR system than a washing machine, as the cleaned load could be left inside for any period of time, whereas wet clothes left in the washing machine became wrinkled.

None of the occupants changed their pre-study washing machine program choices. One occupant considered changing the tariff after coming back from a long journey, but resisted. On another occasion, an occupant noticed that the tariff was on red after having started the washing machine. They switched the tariff back to green, but then decided to let it run on the red tariff, as water had already entered the machine and they were worried that it might start to smell otherwise.

All occupants unanimously considered the tablet more “convenient” than the ‘website only’ option. The main reasons were the ability to change tariffs with ease, getting feedback on price periods and estimating any waiting times. One occupant also highlighted that during the ‘website only’ case study, they were referring to another occupant to get information about the system, as they had difficulties accessing the website themselves. With the tablets on the other hand, they were able to better understand and use the system by themselves.

All three occupants’ willingness and motivations with regards to adopting a similar system on a long-term basis had not changed. However, one occupant indicated that they needed a larger financial incentive, than they stated during the ‘website only’ case study. They also highlighted that they would only use the green tariff for the dishwasher and not for the washing machine, as they would not want to have to wait. Additionally, they suggested, as did another occupant in the post ‘website only’ interviews, that weekend time available to household chores could not be used effectively. Another occupant also suggested that future systems should show energy usage and savings in relation to the chosen program and tariff, either in real time or ideally before the program was started.

4.2 House B

4.2.1 Pre-Case Study Feedback

The House B occupants stated that they used the washer-dryer approximately three times a week, either in the evenings on weekdays, or at different times on weekends. Both occupants used the machine and had their preferred programs. However, one of the occupants considered themselves more responsible for it than the other. The occupants combined their wash loads, but planned to wash their excepted baby’s clothes separately.

One of the occupants indicated that they sometimes thought about the cost and the environmental impact of using the washer-dryer, whilst the other said that neither affected their usage. However, the latter pointed out that they changed energy providers in previous houses for financial reasons and that they considered their current energy price to be average. Both occupants had never used energy display units.

With regards to the prospects of using the proposed system, one occupant judged the website interface as “quite clear, quite simple and user-friendly”. They could both see themselves using a similar system long-term, with one being motived by potentially reduced energy bills, whilst the other found the feedback on current energy prices and the ability to switch tariffs appealing.

4.2.2 Tablet – Case Study

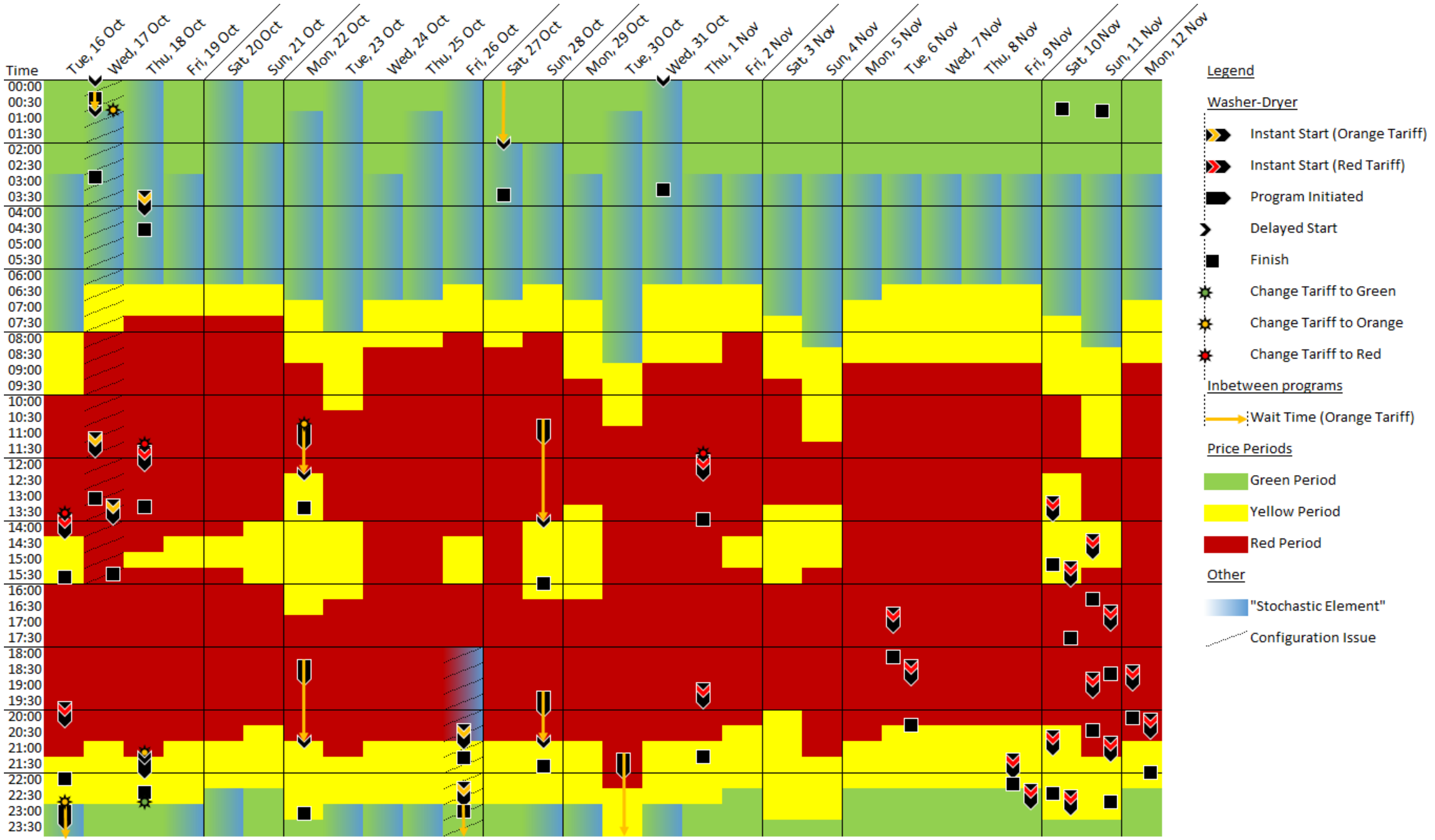

FIGURE 7: HOUSE B – TABLET

Remarks: During the first sixteen days, the house was occupied by one of the two long-term occupants and three guests. After a short vacant period, both long-term occupants returned with a newborn baby on 6th November. As the initially absent occupant was not interviewed before the 'tablet' case study, no post-case study interview was conducted. Instead, the pre-case study interview was conducted with them before the following 'override switch' case study.

The price period data from 16th to 31st October was two days behind the original weekdays. Configuration issues on 17th and 26th October caused programs to behave in an unexpected manner by stopping prematurely or starting to run on the orange tariff during red periods.

On 16th October, after initiating a washing program on the red tariff, the occupant changed the tariff to orange, but as this stopped the washing process, they switched it back to red again. On 17th October, the occupant changed the tariff to red, green and back to orange before the machine started again at the 'stochastic' period at 1:00.

The occupant thought that the system was "quite handy" and suggested that their guests, who were present at the time, liked it too, but that they seemed confused by the orange and yellow tariff choices. Before the guests arrived, the occupant used the red tariff to clean sheets amongst other things. They then changed the tariff to orange, as they deemed that one to have "the perfect time for washing". The occupant highlighted that although a 60 °C washing program with an approximate duration of two hours was used before the study, they now used a 30 or 40 °C program with a duration of 1.5 h, so that it would fit into the available price periods, together with the 0.5 h drying program. The occupant also added that they did not notice any difference in quality of cleaning. However, they pointed out that when they left the house, they would choose the 60 °C program, as they would be unable to initiate the drying program in time.

The occupant initially briefed their guests, as they were using the washer-dryer too. They were thought to have used the orange tariff, as they were mainly out of the house during the day and did their laundry in the evenings. The occupant needed to remind the guests about the system, after it had switched itself off during the afternoon on one occasion. The occupant said that the guests were happy to leave it on orange after that. However, they suggested that a household of five or six people might have difficulties to cope with this system.

The website was thought to be "very user-friendly". The occupant also liked the ability to overrule the system by effectively choosing the red tariff, when something needed to be washed urgently. Furthermore, they believed that the guests mostly did not even notice the system.

The occupant could see themselves using a similar system long-term, with the financial savings as the main incentive. They thought that around £30 a year would make it worth their while. Furthermore, they were enthusiastic about adapting other energy usages around the house to the time varying prices. In relation to future versions of this system, the occupant suggested that appliances should be able to interact with the dynamic prices in order to adapt their internal programs flexibly to available periods. The occupant also suggested that they would be willing to let third party organisations use the collected data.

4.2.3 Override Switch – Case Study

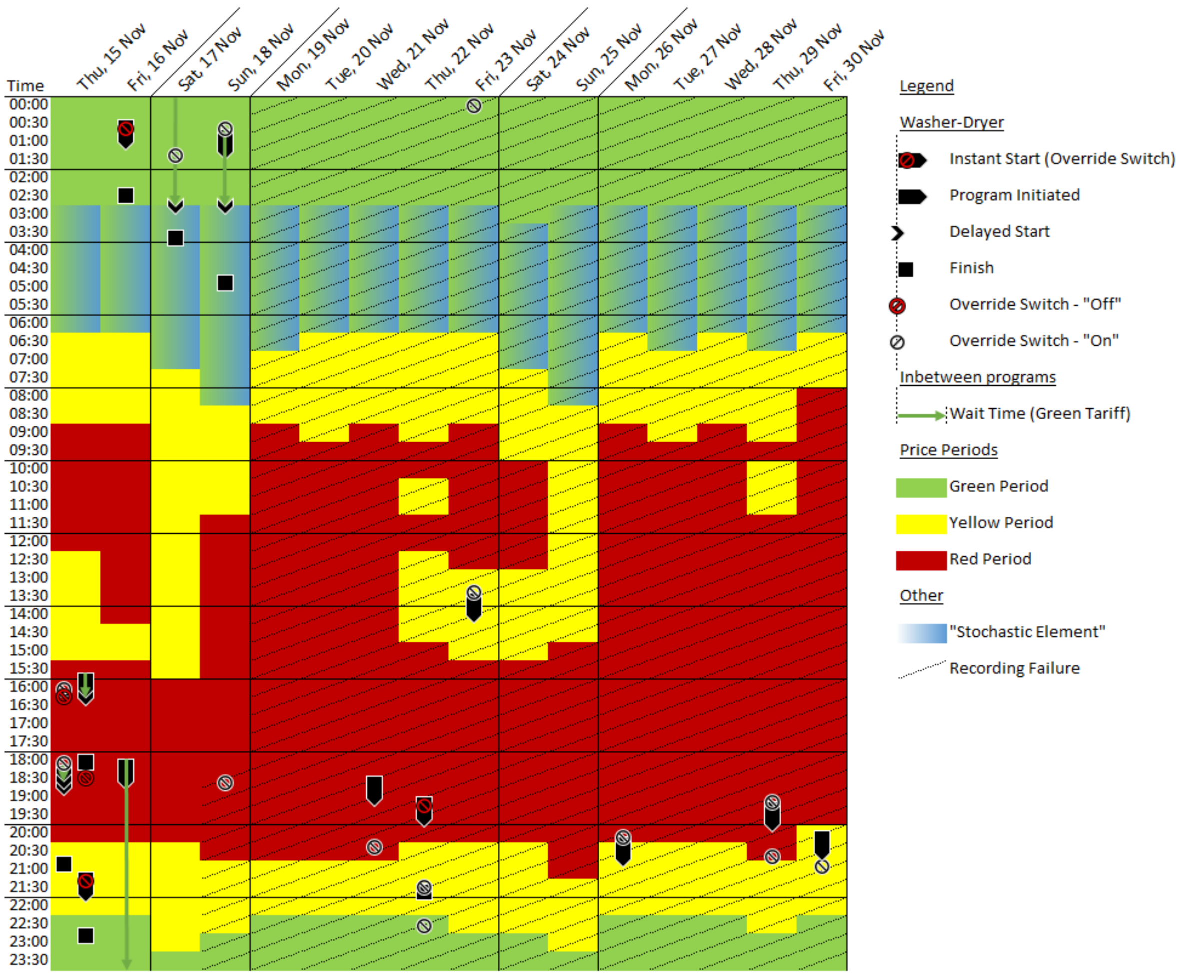

FIGURE 8: HOUSE B – OVERRIDE SWITCH

Remarks: All programs, except the one on 21st November, were initiated on the green tariff. Every time, except on 16th November, the 'on' side of the override switch was pressed before the 'off' side, with time differences of up to 20 minutes. A failure occurred on 18th November, which caused inconsistent recording of subsequent power and tariff data. The sparsely available data was presented in Figure 8, but no assumptions with regards to waiting times were made.

The occupant, who had returned during the previous case study, as reported in Figure 7, was now almost solely in charge of the washer-dryer. However, the interview revealed that this occupant believed that the installed switch needed to be pressed in order to take advantage of the cheaper tariffs. They based this assumption on the fact that the machine did not turn on at least once after they had pressed the button. They also never consulted the website. The other occupant seemed unaware of this situation and believed that the green tariff was being used predominantly. Furthermore, they suggested that the other occupant expected the system to randomly switch the washer-dryer off and that they therefore changed their usual program to a shorter one. Another reason for the shorter programs was the more frequent use due to the added laundry from the baby. However, there were concerns whether that might result in a less clean wash.

The occupant, who experienced both case studies, thought that the override switch was more convenient, as they only needed to set the tariff once and were able to use the button for the exceptional cases. In contrast, although they thought the tablet was too "sophisticated" and took extra space next to the appliance, they pointed out its advantage of showing the daily changes in price periods. Furthermore, the occupant indicated that checking the price periods on the computer was an extra effort during this case study, and that therefore assumptions were made once the machine had been started, based on whether the system allowed it to run or not.

This kind of system was seen as a possible long-term option, especially as the occupants desired price periods matched the time they usually used the machine. As their lifestyle was not affected, no specific amount of financial savings was required as incentive. However, "five or even three percent" of savings were deemed good. One of the occupants also highlighted that this kind of system might not be convenient to a household, which has a person staying at home during the day. With regards to improvements, the occupant who experienced both interfaces suggested that an LED screen, which indicated the duration of the current price period, could be an alternative interface option to the tablet, and could be used in conjunction with the override switch.

4.3 House C

4.3.1 Pre-Case Study Feedback

For House C, the pre-case study interviews revealed that the washer-dryer was used mostly in the evenings on weekdays and throughout the day on weekends. The choice of washing program depended on the material of the clothes and on whether they were the child's clothes. The occupants stated that they use the machine between three and seven times a week. One occupant was primarily in charge of operating the washer-dryer.

Both occupants mentioned that they were aware of the cost and the environmental impact of the appliance, but one highlighted: “If I have to clean, then I don’t think about the cost, I just think about cleaning”. In addition, the other occupant pointed out that they received their energy bill once a year, which they thought was inadequate in terms of feedback. Concerning potential energy savings, one occupant indicated that they were not aware of any further saving potential. They also mentioned that there was no space in the house to dry their laundry, which effectively forced them to use the drying function of the machine.

Both occupants stated that they had never used an energy display to monitor their consumption. With regards to the prospects of using the designed DR system, one occupant liked the extended control, whilst the other found the feedback appealing. However, there were also concerns that the system might break the washer-dryer.

They both liked the overall concept and could “see a lot of people using it” long-term, including themselves. One incentive was the ability to remote control initiated programs. Though one occupant pointed out that the financial savings would need to be large enough to compensate for the loss in flexibility, mentioning a figure of 10 %, which they estimated to be equivalent to £80 a year. In addition, one occupant suggested that a developed version of the DR system should present the user with the expected financial savings for when only the lowest energy price periods were used.

4.3.2 Website Only – Case Study

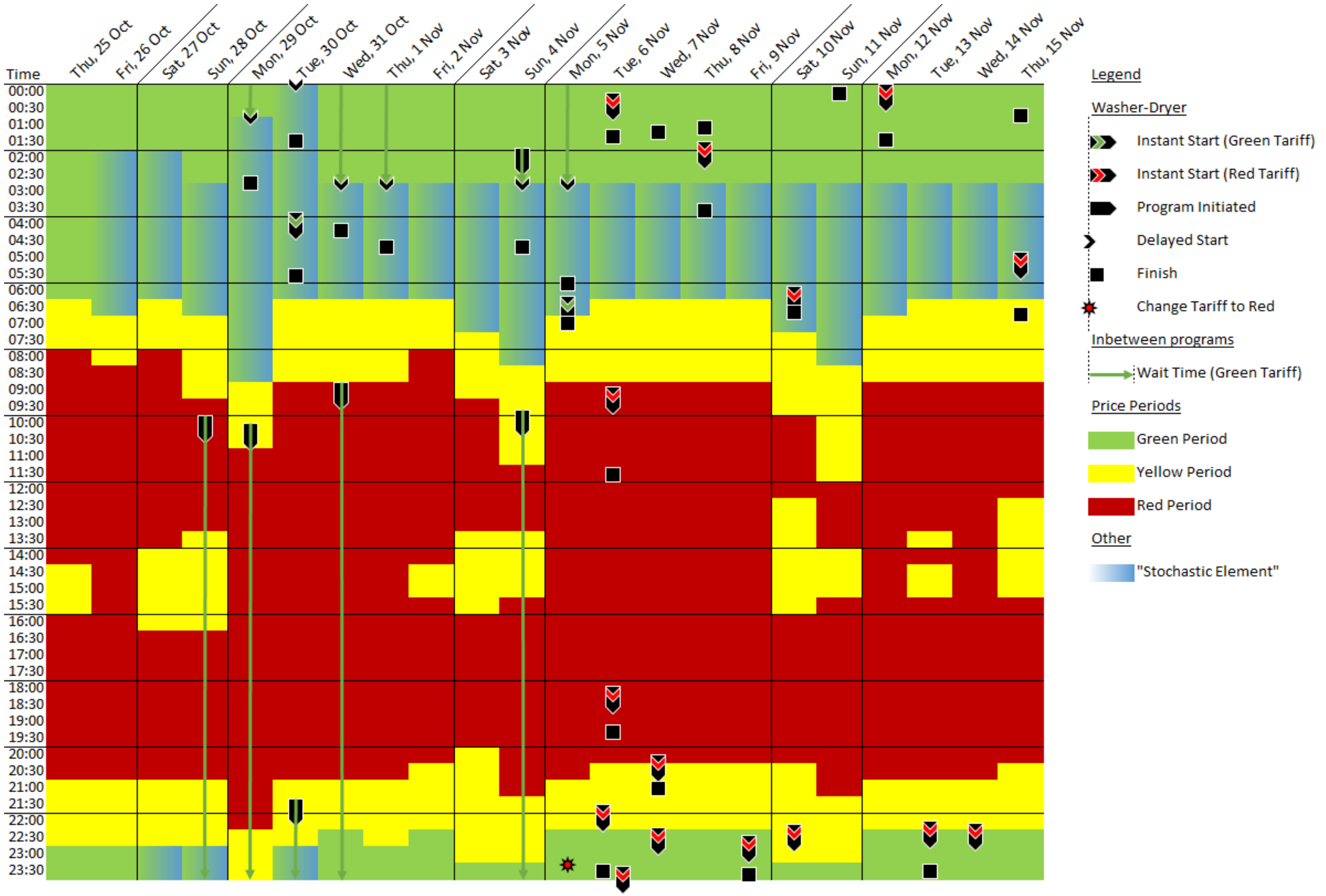

Figure 9: House C – Website Only

Remarks: In the middle of this case study, one occupant left for a short period of time and returned with a newborn baby. The price period data from 25th to 31st October was one day behind the original weekdays.

The post-case study interviews revealed that the occupants did not feel comfortable with the DR system. They thought that it was inconvenient. One occupant pointed out that they were unable to plan ahead, as it was not possible for them to tell when the machine would come on. When they chose the green tariff, the washing program would start around 1:00 or 2:00 and would finish around 6:00, although other times were shown on the website interface.

Both occupants stated that this reduced amount of time was not enough for them to do their washing, especially as they had no space to dry their clothes and therefore needed to separately run a drying program on the washer-dryer. This effectively meant that it took them two days to wash and then dry their clothes. It was pointed out that one of the occupants had to wake up in the night to put on the drying program.

As the lost time created a backlog of washing, they decided to change the tariff to the red one. However, one occupant highlighted that they wanted to "leave [the green tariff] on for at least a week to see exactly what happens". Both occupants mentioned that they expected a considerably greater amount of green price periods on the weekends. Also, one occupant seemed surprised that green price periods did not start earlier in the evenings.

One occupant liked that the system did not change the way the machine was operated and thought that the current difficulties with the system could be related to the fact that they were not used to it. The same occupant would consider adopting a similar system on a long-term basis under the conditions that the price periods were different and that the cost savings would be around 50 %. However, the other occupant would not want a similar system, even if it was associated with substantial cost savings, as the lack of control was perceived as a substantial hindrance.

With regards to future systems, it was suggested by one occupant that washing programs could be divided into smaller parts, so that they can be run throughout the day. Another suggestion was to let the system decide whether to let a program run or not depending on its accumulated cost and its temperature setting. The other occupant proposed the ability to choose when the green periods occurred. Theoretically, both occupants did not mind sharing the collected data with third parties.

4.3.3 Override Switch – Case Study

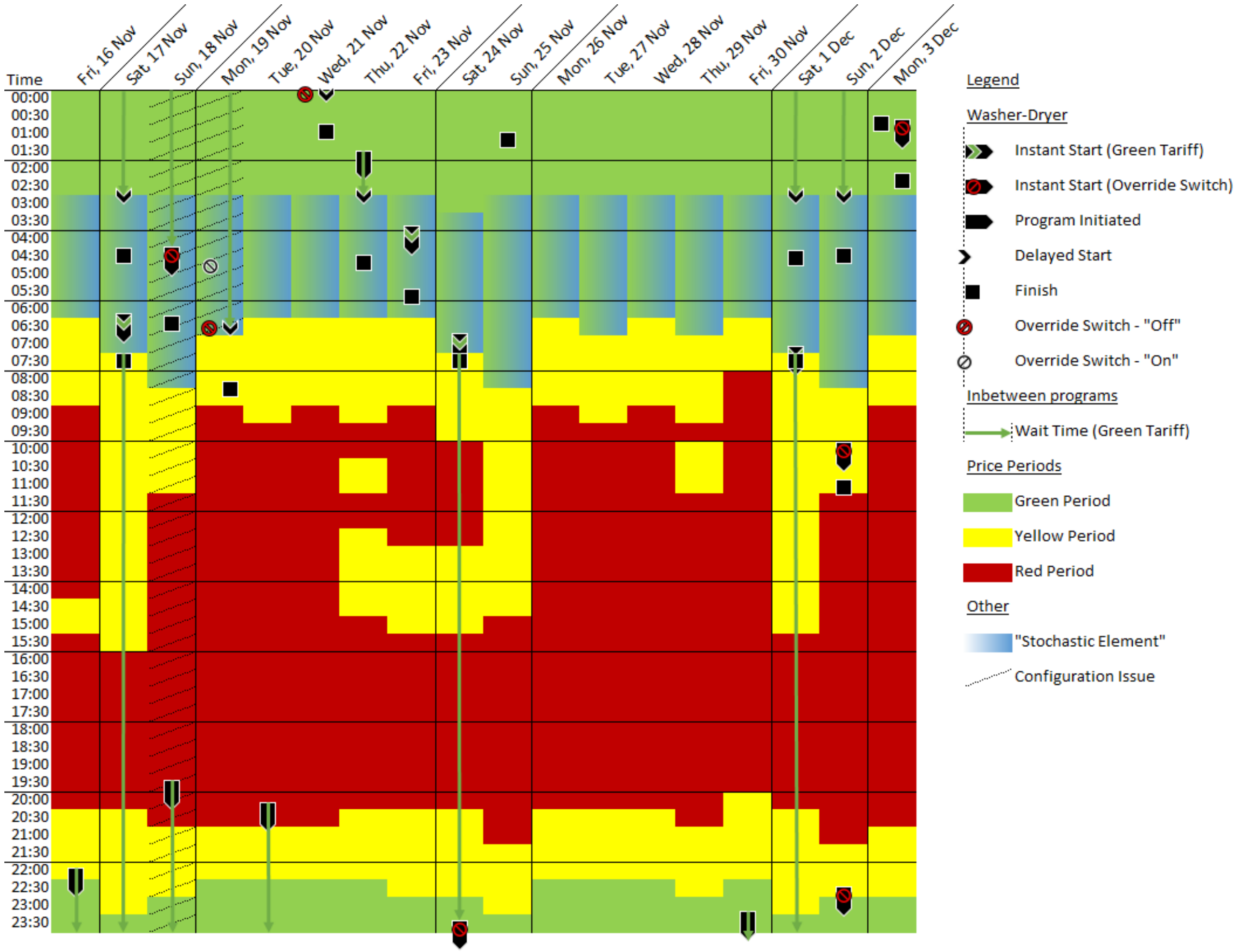

FIGURE 10: HOUSE C – OVERRIDE SWITCH

Remarks: Configuration issues on 18th and 19th November resulted in programs not starting automatically; hence, the occupants had to press the override switch to start the programs manually. On 3rd December, the washing program was initiated before the override logic could reset itself, which resulted in the program starting immediately.

The ‘override switch’ case study was perceived as “much better” by both occupants compared to the previous ‘website only’ case study. However, at least one occupant seemed to believe that the override switch replaced the website interface, rather than being an add-on feature, as they mentioned that they were missing the ability to switch tariffs or see which one was currently being used. They also pointed out that generally not enough feedback was provided with this setup, with regards to when the machine would start operating after its initiation.

The other occupant found the system “not difficult to use”. To prevent a backlog of washing, they used the washer-dryer during the week on the set tariff and on weekends they used the override switch, because the child’s uniform needed to be washed and dried.

Also, the change in interface improved one occupant’s opinion of the system, as they could “wash something quickly” by using the override switch. They highlighted that they knew about the difference in cost, but that sometimes there was no way around it. They were more motivated to adopt this kind of DR system long-term, than they were after the ‘website only’ case study. However, they suggested that better feedback with regards to predicted financial savings was required and proposed to exclude Sundays from the dynamic RTP scheme.

The other occupant was very hesitant about whether or not to use this kind of system long-term. They liked the fact that programs could be postponed, but felt that more control was needed. They suggested that being able to choose the exact time when the machine would come on during green price periods would be a potential improvement.

5 DISCUSSION

The data from the focus groups and the case studies showed the complex relation between participants and domestic DR systems. A variety of factors influenced the acceptance level of the proposed system, including amongst others the incentive, feedback and control mechanisms.

It is worth noting that the case studies’ findings alone do not allow for generalisation, as the sample size, sample characteristics, duration of the study, and fictional pricing scheme are not statistically significant or representative of the wider population. However, the findings which are corroborated by the focus group study or other research, can help identify gaps, particularly with regards to the themes of ‘users and the use of the smart home’ and ‘challenges for realising the smart home’, as described in [32].

5.1 Incentives

Within the theoretical consideration of DR during the focus groups, participants stated that they were incentivised by financials gains. Though, it subsequently transpired that social dependencies and convenience would have priority in most cases. Similarly, in the real-life setting of the case studies, the majority of participants stated at the beginning to be incentivised by financial savings, with the amounts varying significantly, i.e. from 3 to 50 % of annual electricity costs. However, throughout the course of the two case studies, most participants increased the amounts required for DR system adoption under its presented form and made it conditional, as highlighted in section 4.1.3. Furthermore, a lack of control and feedback can lead to total disengagement, whilst enhanced convenience of controlling the automation system, as perceived by one of the House C occupants, see section 4.3.3, directly improved the hypothetical adoption of the DR system as a whole. This suggests that financial incentives are ideal for attracting potential users; whilst convenience related incentives, including ease of system operation, will determine user retention. These findings are also consistent other research in this area [12,33].

5.2 Feedback and Interface

Due to a perceived lack of feedback, participants decided to make assumptions with regards to which tariff they were using or how the overall system was working, as mentioned in section 4.2.3. This highlights the importance of feedback and that the internal household dynamics are crucial in relaying information and training co-occupants. As highlighted by the focus group results, the entire household is involved in the shaping of a given practice. Hence, consideration should be given to how the entire household can be engaged or how targeted information and skills can be transferred to individuals. Similar findings have been reported in other fields [34], however, further work on this particular topic is needed in relation to in-home energy management systems.

Furthermore, actual lacks of feedback from the DR system, e.g. shortened appliance cycles and pre-maturely starting washing programs, see Figure 10 - 1st and 3rd December respectively, meant that the user was not explicitly informed and was therefore required to perform additional verification tasks to ensure that the system was operating correctly, which would not have been required without automation. If the user did not take on this responsibility, their clothes may not be as clean or dry as expected, or they end up using energy during expensive periods. Investigating this change in workload and management resulting from DR systems, especially in the context of inherently ‘smart’ appliance, could be addressed by future research studies.

It is worth noting that the levels of control and feedback were not restricted during the case studies. Throughout, all participants had access to the tariff control and price period feedback via the controller's web interface. However, as the different case studies demonstrated, the proximity between the operated appliances and the user interfaces, which provided the control and feedback, played a crucial role. Hence, the 'tablet' and the 'override switch' were distinctively preferred over the 'website only' solution. With regards to a preference between tablet and override switch, the House B occupant, who was the only one to experience both, seemed to prefer a combination of both. This aligns with the findings of the focus groups, see section 3.2, as there is a clear purpose and agency associated with the nearby interfaces.

Also, the website interface was deemed by the majority as user friendly during the pre-case study interviews. However, one participant mentioned that they did not know how to change tariffs in section 4.1.2, and another accidently changed the dishwasher tariff instead of the washing machine tariff, see Figure 5 – 8th October. Therefore, besides the proximity, the clarity of the user interface should be considered during future DR implementations. This also resonates with focus group results and other research [35], which pointed out that kWh is not a metric with innate meaning and that simple and intuitive representation of information is more effective.

In addition, reliability of feedback is required to allow users to plan ahead, as pointed out in section 4.3.2. Particularly, as it was shown that the wider context affected how the appliances were operated. Factors, such as weather, available drying space, urgency of needing the clothes cleaned, noise generated by the appliance or ancillary systems, such as the rainwater pump and available renewable energy, all influenced how focus group and case study participants operated their machines.

5.3 Control and Behaviour

The appliances themselves also affected the operation process of the DR system. Although the majority of participants liked that the appliances could be used in the same way as before the study, they did point out that an appliance's separate initiation of two subsequent programs could result in two nights being spent on a single washing and drying cycle. In this context, the occupants of House A developed a coping mechanism, which meant that they operated the dishwasher's pre-wash program on the red tariff, whilst running the main washing program on the green tariff, as shown in Figure 6. However, with washer-dryers having longer program times, House C occupants coped by waking up during the night to initiate subsequent programs, as shown in section 4.3.2, which would be unsustainable over extended periods of time.

Furthermore, the choice created by the DR system, between saving money and losing time, was shown to impact the internal dynamics of households. House A occupants, who had no washing routine before the case studies, employed a rota to maximise the usage of the lower price periods, as described in section 4.1.2. However, larger households might not be able to cope with this limited availability, as suggested by House B and C participants.

In contrast, the mentioned constraint also yielded energy saving behaviours, with one House A occupant developing the new habit of checking the washing machine in the mornings, which meant that wet clothes were not forgotten about and hence did not need to be re-washed due to their smell. Another participant purposely shortened their programs to the available time slots, as mentioned in section 4.2.2, which made them reduce the temperature of their washing programs and thus the cycle's energy consumption.

However, the results also suggested that a dynamic pricing scheme, as the one implemented, may occasionally increase energy usage or decrease performance. As programs were interrupted when price zones ended, e.g. see Figure 10 - 24th November, participants may needed to restart the same program from the beginning; or if they did not notice that the program was pre-maturely interrupted by the automation system, their clothes may have been insufficiently washed or dried. This suggests that careful consideration needs to be given to future automated DR algorithm designs to strike a balance between price adherence and system performance.

Furthermore, several participants pointed out that the dynamic electricity prices were restrictive on weekends, when they had time for chores or needed to wash the children's uniform for the next week. Hence, some suggested an improved coordination between appliances and pricing schemes, whilst others suggested pre-booked periods or exceptions for weekends.

5.4 Ownership and Trust

All of the case study participants were theoretically willing to provide third parties with the data generated by the DR system. However, the fact that they lived in experimental houses and were to some extent involved in associated research work, as outlined in section 2.2, may carry a bias. In fact, the focus groups and other similar research [12] did highlight a general distrust towards the energy industry, which suggests that others would not be as willing to share their data.

Focus group participants were also concerned about involuntarily abdicating autonomy and by extension ownership, as mentioned in section 3.3. This was in line with some of the case studies, where the participants felt constrained by the system to the point where they chose the red tariff to effectively regain their autonomy. In House A, however, the introduction of DR actually encouraged individual users to take more personal ownership of their washing practices, leading to new skills, such as effective time and energy management.

6 CONCLUSION

The study provided an overview of the complex relations that need to be considered during the design and implementation of domestic DR. Generally, DSM aims to optimise energy usage by providing financial rewards. However, on a household micro-ecosystem level, time and space were shown to be two very important resources that also need to be co-managed by the system. Similarly, practices, such as preparing for the day or week ahead, were prominent in participants' decision making and their vision of future DR systems. The study therefore suggests that financial incentives might be effective in attracting potential DR users; whilst convenience and social dependencies will determine user retention and satisfaction.

The levels of control and feedback provided by the DR system were crucial too, with regards to user acceptance. The proximity, clarity and reliability of the interface, as well as its inherent agency for the user, influenced participants' interactions with the automation system and hence directly affected the exploitation of energy saving potential. In addition, appliance's features and the wider context they were operated in determined their performance once automated, and by extension the acceptance of the DR system.

It was also demonstrated that participants can quickly develop behavioural changes and coping mechanisms to adapt to the constraints introduced by the dynamic pricing scheme. However, it was pointed out that limited availability of low price periods might strain household dynamics and could cause efficient as well as inefficient energy usage in conjunction with automation. Furthermore, household internal communication structures were found to affect the adoption of the knowledge and skills required to operate the DR system; some of which were inadvertently introduced by the system itself, adding to the user's responsibilities and workload.

Future work could further examine specific aspects of the broader concepts discussed, for example by investigating the integration between a set of active and passive DR users, inherently 'smart' appliances and building environment features. Studying these complexities in the context of new or retrofitted ultra-low energy houses could provide valuable insights into how systematic change to a net-zero society could be effectively enabled.

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Appendix A Pre-case study interview questions

Existing Behaviour

- When do you currently use the dishwasher / washing machine?
- Do you typically use the same program, if so which one, or do you vary them?
- Do you coordinate with your housemates when using the appliance, or each use it separately?
- Is there someone in the household that typically takes charge of the dishwasher / washing machine?

Price/Environmental Sensitivity

- Would you currently consider your energy bills to be low, average or high?
- Do you consider cost, the environmental impact or both when using the dishwasher / washing machine?
- Have you ever done anything to try and reduce your energy bill or use – like change providers or limit usage?
- Do you currently or have you ever monitored your energy usage with an energy display?

Technical Literacy

- Do you feel confident using computers and other digital devices?
- What are your first impressions of the web interface?

Overall Interest

- Can you see yourself using such a system on a daily basis?
- Do you have any concerns about using the system?
- Do you find anything appealing about the system?
- What would incentivise / encourage you to use such a system?

Personal

- What is your age?
- What is your profession?

Appendix B Post-case study interview questions

General

- Can you describe your experience of using the system?
- Is there anything you particularly liked/disliked?
- Did the system prompt you to change how you used the machine (e.g. programme choice or time of use)?

Household Dynamics

- How did you handle usage of the system among you and your guests?
- Did it ever prompt you to change your routine, or habits?
- Were there any disagreements? How did you handle those?
- Did the system provoke any particular discussions?

Enhancements

- Did the system work as expected?
- What could be done to enhance the system?
- What should be retained?

Continued usage

- Having now used the system, would you consider using it long term?
- What would need to be in place to encourage you to do so?
- How much would you need to save to continue using such as system?
- Would you allow others (e.g. government, private companies, charities, academic researchers) to access energy data that is stored by the system?