Accounting for Energy-Reliant Services within Everyday Life at Home

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Abstract. Researchers in pervasive and ubiquitous computing have produced much work on new sensing technologies for disaggregating domestic resource consumption, and on designs for energy-centric interventions at home. In a departure from this, we employ a service-oriented approach, where we account for not only the amount of resources that specific appliances draw upon, but also how the associated services may be characterised in the context of everyday life. We undertook a formative study in four student flats over a twenty-day period, collecting data using interviews with eleven participants and over two hundred in-home sensors. Following an in-depth description of observations and findings from our study, we argue that our approach provides a more inclusive range of understandings of resources and everyday life than has been shown from energy-centric approaches.

1 Introduction

Prior sustainability-related research in the field of pervasive and ubiquitous computing has most often focused on novel sensing technologies and algorithms (typically aimed at resource disaggregation to the end appliance or tap [5]), or on exploring the conservation potential of technical interventions (e.g. electricity monitors placed in homes). In either case, the area of focus has been on either measuring, or utilising such measures of *energy consumption*. However as Shove points out, "relevant patterns of consumption follow from efforts to provide and sustain what people take to be normal services like those of comfort and cleanliness" [14, p. 198]. Thus, this paper takes an approach departing from prior work in pervasive and ubicomp: to describe energies only alongside the wider context of the *services* in which they are bound up. As background (section 2), we argue that the rationale for this approach is because services are much more relatable to everyday life.

Before proceeding, we should define what we mean by "service". As the above quotation from Shove implies, many services in the home are built up and maintained in the pursuit of comfort and cleanliness. Such services might be heating, lighting or food preparation (cooking). In addition to comfort and cleanliness, we would also add that services (such as those provided by information technology) may support expectations for play and work at home. In any case, *services* are "composite accomplishments generating and sustaining certain conditions and experiences... services have to do with the orchestration of devices, systems,

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expectations and conventions" [14, p. 165]. Thus, to comprehensively describe a service, we should consider not only the resources (energies) necessary for its upkeep, but also the appliances, infrastructures, social norms and human action, within which the service is bound and reproduced.

The thesis of this paper is that compared to an energy-centric approach, a service-oriented analysis creates a more inclusive, nuanced and well-rounded understanding of the relation of resources to everyday life at home. Such an analysis necessarily relies upon both qualitative and quantitative data, in order to be able to frame the services in the context of their associated practices, expectations, energies, infrastructures and appliances.

Putting the service-oriented analysis to work in a case study, **our primary contribution is to give an account of how three services are composed and maintained in four homes, and the insights relating to resource intensity that arise from this.** Through the exposition of our accounting exercise, a secondary contribution is to consider possible pervasive sensing solutions appropriate for gathering data contributing to understandings of service components. Following a description of our participant flats and accounting methods (section 3), and the characterisations of service in this case study (section 4), we take a step back and identify the advantages of our service-oriented approach and consider possible limitations (section 5).

2 Background

As has been previously discussed [4,11], much of sustainability-related research in ubicomp and HCI has been concerned with estimation and display for consumption feedback approaches. While the 5–15% reductions [3] historically associated with feedback-based interventions are not insignificant, Pierce et al. [10] highlight that very little is known about the changes implicated with these reductions, and how the reductions relate (or not) to particular types of feedback.

Strengers [16] developed the critique that eco-feedback systems are "grounded in a basic assumption that home dwellers lack information" [10, p. 244] which presumably is required if they are understood as "micro-resource managers" [16, p. 2135]. Strengers argues that such assumptions result in problems best characterised by a disconnect between the types and methods of feedback, and "the realities of everyday life." As Strengers poses, solutions might be to offer less data-oriented forms of feedback; target "non-negotiable practices" and changing expectations by making and sharing practical recommendations and knowledge; and encourage debate about what is normal and necessary. To support such goals, researchers and designers need to understand everyday life: "what people do in their homes, how people use energy and water and why" [16, p. 2142].

We would argue that consumption feedback is but one instantiation of *resource-centric* approaches more generally; another class might be demand-side investigations of consumption. Such framings tend to base the focus of enquiry tightly around quantitative measurements of resources such as electricity, natural gas, or water. Many of the above points about consumption feedback apply to resource-centric approaches more broadly: without a framework that factors in people's habits, expectations, and interactions with devices and infrastructure (all part of everyday life) then the resulting understandings are narrow. This reflects wider literatures on energy and consumption studies [13]; part of a process of connecting the development of sensing and interaction to other domains and theoretical approaches [1], which we view as essential to achieve more inclusive accounts of domestic resource-reliance and sustainability.

Moving on, what would a more inclusive framing be? One analytical trick borrowed from sociology is to de-centre the user and consider the activity or practice [18] taking place. Identifying a practice and what shapes it is one way to think about "engag[ing] with social and cultural dynamics" of everyday life. In place of a concept in which people consume energy, we could suggest that practices consume resource-reliant services. A service-oriented analysis, then, may be a suitable way of understanding the quite indirect connections between resource consumption and practice. The concept of services (defined above), encompasses varied components, requiring both a qualitative and quantitative investigative approach. Hybrid qualitative/quantitative methods have been proposed by others looking at sustainability, but from different directions [6,8,15].

Aspects of our study echo those of certain previous formative studies of current practices [12] but with two distinctions: (i) we do not seek to understand human action or attitudes related to energy *per se*, but rather as practices in which energy-reliant services are consumed, and (ii) we gather energy (electricity) data as a quantification of the resources involved. The method we pilot might also be used by researchers to evaluate eco-feedback systems: addressing the lack of knowledge [10] about the nature of any changes they create.

3 Methods

Like Hayes and Cone [9], our target was shared student accommodation on a university campus. We chose to focus on this specific population for two reasons: (1) they are in close proximity to our research building, which meant that it was convenient for us to conduct and monitor the sensor deployment, and make ourselves readily available to our participants; and (2) because of an existing university initiative, we had access to historical energy readings for on-campus flats. Since we are interested in understanding the reasons for resource variations in different homes, the per-flat historical data allowed us to recruit participants in flats whose measured consumption was high-average or low-average, but not extreme. Our participants are undergraduates, many in their final year of study, of mixed gender and subject specialism.

We studied four flats for a duration of twenty days. Each flat was composed of eight individual study bedrooms, two showers, two toilets, and a kitchen, arranged around a central corridor. We used sensors (see below) to monitor the shared areas in all flats, and twenty-two participants agreed to have their personal bedrooms instrumented (3, 8, 5 and 6 bedrooms in each flat). We conducted face-to-face, follow-up interviews with eleven of the participants, and solicited near-time ‘mini-accounts’ (answers to a small number of short questions posed by SMS or email during the study). We refer to the flats as Green, Blue, Red and Yellow and give participants pseudonyms to preserve their anonymity.

Fine-grained, whole flat electricity readings are logged from OWL brand electricity meters. We use a Plugwise “Circle G” to log power at each socket—four per study bedroom, two in the corridor and nine in the kitchen. Participants were asked to treat the device as they would a normal socket. We noted the mapping from sockets to appliances where possible, although some sockets were connected to multiway adapters and hence may correspond to multiple appliances.

To capture cooking activity we mounted a motion-triggered wildlife trail camera (*the hobcam*) above the cooker (also known as a “stove” or “range”), looking down at the hob (or “burners”). Since the cookers were wired directly into the mains, we were not able to directly measure their energy using Plugwise. The energy for each cooking session is identified by correlating data from the OWL meters with the start and end time of the cooking session. The start and end times are derived from the timestamps on the hobcam images, corrected by visually inspecting each session and making fine adjustments using a time-series plot of the high-frequency (six-secondly) OWL data. The cooking session energy is computed by subtracting the total socket energy, and an *energy baseline* averaged from a 30-minute window either side of the session (to account for unmetered devices) from the whole flat consumption.

We deployed MS13E2 “Hawkeye” motion/light sensors (X10 wireless) in each bedroom, shower, corridor and kitchen. These help to disambiguate active and passive use in study bedrooms, and use of the shared areas. The motion/light sensors are only capable of capturing binary representation (light/dark, and motion/no motion) in each room.

Each flat had its own data logging PC connected to an RFXCOM receiver and a Plugwise “Circle+” node. We use Domotiga,[1] an open source home automation software package to decode the X10 and Plugwise packets.[2] We subtract the load for the data logging PC and Plugwise units from our analysis. In total 129 Plugwise, 42 motion/light sensors and 38 temperature/humidity sensors were used in our deployment across the four flats.

Limitations and Assumptions. We gathered data from a relatively small, very specific set of participants: thirty-one students at a UK university in shared institutional accommodation. As is typical for micro-level studies of a small number of homes, some of our findings will be highly localised to our participants, while other findings may be more generalisable. Regardless, this does not detract from our ability to demonstrate what a service-oriented analysis can expose.

We were not able to measure lighting energy directly, so we assume the following minimal model: at night (between local times for sunset and sunrise) we attribute energy to lighting whenever a sensor reported light in bedrooms. We assumed the light source to be the ceiling light of known power (72 W). We

[1] `http://domotiga.nl/`, accessed 28 February 2012.

[2] Plugwise is closed-source and uses a proprietary protocol partially reverse engineered by the home automation community.

ignore other possible bedroom light sources such as desk lamps. During the day, we assume that only 20% of the bedroom lighting time is due to the ceiling light (although from testimony we know it was common for curtains to be drawn and the ceiling light to be on, during the day). The shower rooms had no windows, so we attribute light (20 W) and fan (35 W) power for the durations that the light sensor reported light, day or night. We further assume that the corridor lights (64 W) are on only when both corridor light sensors activate simultaneously. Toilets were not monitored in our study, so we assume the light (20 W) and extractor fan (35 W) in each toilet are active for two hours per day, which from participant accounts seems conservative.

There were instances where Plugwise sensors failed to report, yet were known to be under constant loads, for example in a Blue bedroom a PC and amplifier (combined 240 W) were left on continuously. In such cases (shown as shaded regions in figures 1 and 2) we were able to reinstate the data by interpolation. We measured the various appliances in a range of operational modes during our follow-up analysis to verify this approach. In any case, none of our findings rely solely on analysis of such reconstituted data.

For unmonitored bedrooms, we estimated the appliance energy based on what we knew about the devices in those rooms, and the reported Plugwise data for monitored rooms with similar sets of appliances (e.g. 4.4 kWh for rooms with a single laptop, and up to 29.0 kWh for those with entertainment systems). The lighting in unmonitored bedrooms is assumed to be in the lower quartile of lighting estimates from similar rooms (4.8–8.7 kWh). We do not use the unmonitored bedrooms' estimated energy in any of our findings; they only appear in two figures, purely for the purposes of visualisation.

We label any remaining unexplained energy between our fine accounting and the OWL flat aggregate as "dark energy". It is additional energy from the unmonitored bedrooms, use of devices not reported by Plugwise, and additional lighting not in our conservative estimates. By far the largest proportion of consumption we monitored in bedrooms is attributable to entertainment, IT and lighting, and we have seen nothing in the sensor data or participant accounts to suspect that anything outside of these contributes significantly to dark energy.

4 Findings

Our service-oriented analysis begins with the resources (figures 1 and 2): in terms of electricity-reliance, the three most significant services are those of entertainment and IT, lighting, and food preparation and storage (i.e. cooking and refrigeration). Although our participants discussed some energy-reliant services that do not fit into these three categories (e.g. grooming or cleaning), we do not include a discussion of these due to their vanishingly small total energy. For each category of service, we will report on its energy attribution, the associated practices, appliances, and expectations. We will then discuss opportunities for making effective changes within the provision of these services, and the potential role of sensing in accounting for that service.

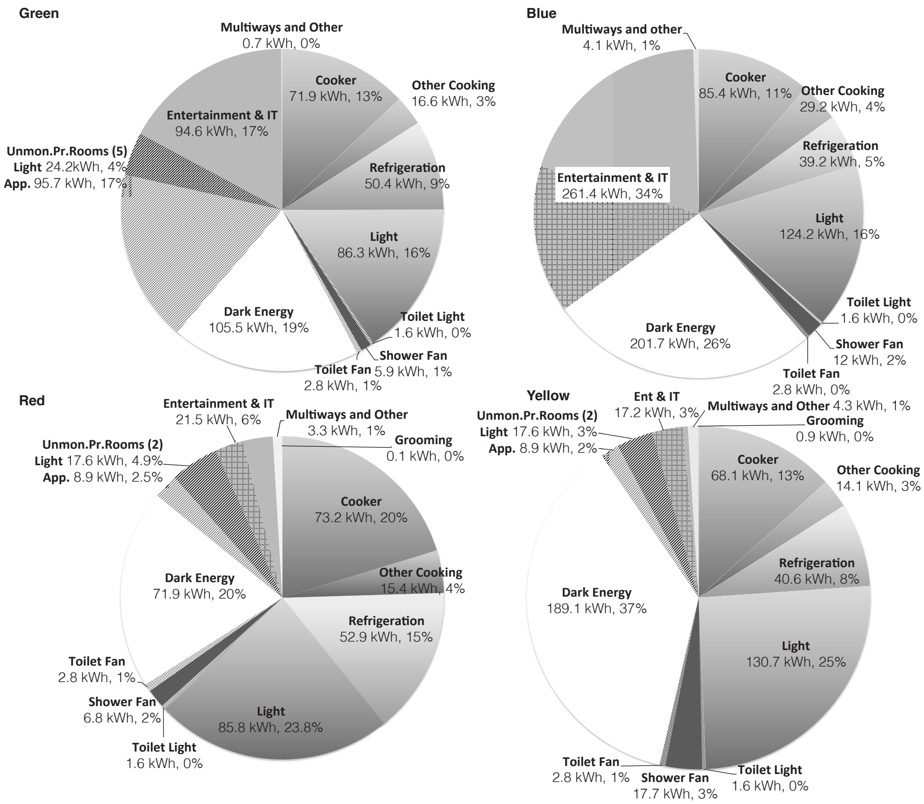

Fig. 1. The relative energy breakdown of the flats over the twenty days. Shaded regions indicate where we have reconstituted data or made minimal assumptions (see section 3).

4.1 Entertainment and IT

We begin our investigation with the most variable of the services we observed: entertainment and IT. This class of service accounts for 3.5%–34% of a flat's total electricity consumption (figure 1)—ranging from 17.2 kWh to 261.4 kWh in absolute terms (figure 2). To analyse how this energy-reliant service is composed, we first look to the device inventory taken in the participant bedrooms. Generally, most participants owned a laptop; two had both a desktop PC and a laptop; and one had a PC only. None of the female participants possessed a PC, and compared to the male participants, they had few other entertainment or IT devices (a printer, a games console, a TV, an iPod dock). Conversely, nine of the twelve male participants had extra audio, video or gaming devices, and five of these possessed more than one of these devices.

Device presence correlates with a room's energy level. For example, none of the PCs, audio, video or gaming devices were identified in Red. Blue, the domicile with the highest entertainment and IT energy, contains two always-on PCs acting as servers, and all four male participants have audio, video and

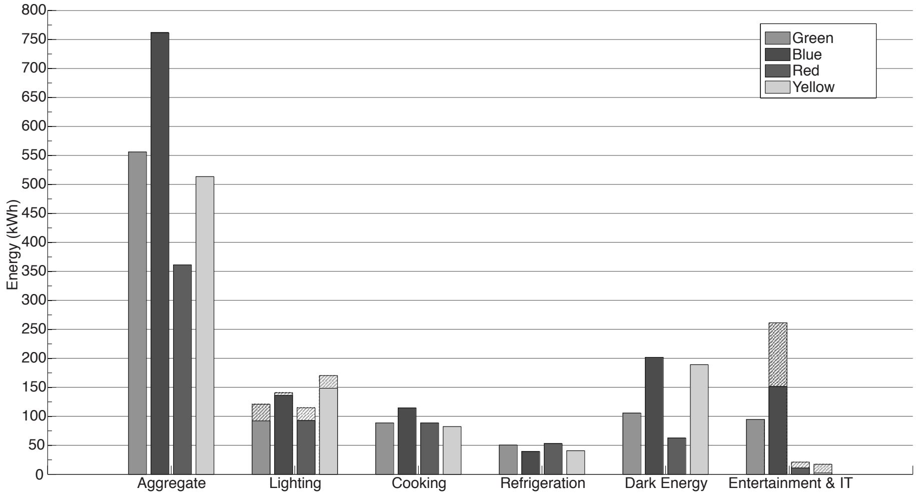

Fig. 2. The absolute energy consumption of the flats. For lighting, shower fans are included, and the upper shaded part of the bars represent our energy assumption for the toilets (light+fan) and unmonitored bedroom lights. For entertainment and IT, the shaded parts represent where we have reconstituted the Plugwise data for appliances in that category.

gaming electronics. In Green, Henry's room accounts for most of the energy in this category (61.8 kWh compared to 18.5 kWh and 6.3 kWh for Callum and Leah, respectively). Henry owns a sizeable collection of IT and peripheral devices. Yet for Yellow, consumption is lower than we would expect given our initial inventory: three of the male participants had some combination of audio, video and gaming devices. It is possible that Plugwise sensors were unplugged or faulty and missed some of this consumption—contributing to dark energy in this category.

Of course, the presence of a device is only an indication of its actual use. The data showed that the duration and frequency of use of PCs and laptops varied: some were characterised by periods of discrete and distinct use, whereas others appeared to be on for the majority of the deployment period. PCs commonly have an array of power management settings, such as *on*, *off*, *standby*, and *hibernation*. Laptops are more complex, including an additional *charging* state, which consumes energy, and they have the option to be powered from battery: this makes assumptions about the state of activity of a laptop difficult. For entertainment devices, such as televisions, amplifiers and gaming consoles, the power management functionality is generally less complex (*on*, *off* and *standby*).

Table 1 details the daily energy consumption of participants' laptops, where it was possible to distinguish them from other devices. This illustrates that the resulting consumption can vary considerably: for example, Miranda's laptop consumed twice the energy of Aaron's. While it is not surprising that the power requirements of various laptops differ [19] (Aaron's consumed up to 65 W to

Table 1. Energy breakdown for nine bedrooms

Participant	Flat	Energy (kWh) Entertainment & IT (Laptop)	Other	Lighting
Aaron	Red	2.64 (2.64)	0.13	8.32
Thomas	Red	9.92 (9.92)	0.26	12.69
Callum	Green	18.45 (4.17)	0.09	9.6
Henry	Green	61.75	0.148	10.97
Leah	Green	6.29	0.3	11.94
Ellie	Blue	2.9 (2.9)	1.39	6.5
Feng	Blue	9.34	0.21	6.74
Miranda	Blue	5.28 (5.28)	0.068	5.33
Rachel	Blue	4.83	0.41	11.28

Miranda's 40 W), we see that patterns of use vary considerably: consistent with previous findings in US homes [2], our participants exhibited variety in using and managing their devices. Miranda's laptop was "on" in a state that draws around 10–15 W for two or three days at a time, whilst Aaron's regularly consumed under 5 W. To understand this difference, we need to turn to the interviews. Miranda reported that her laptop was, in fact, broken: it wouldn't charge. Because of this she leaves it plugged in all the time, and for fear that it won't start up again, she never turns it off; she just closes the lid. Interestingly, Aaron's laptop is also broken but there is one, potentially decisive difference: whilst he leaves it plugged in to the power supply so that it will also be charged if he needs it, Aaron, unlike Miranda, will shut it down "*every time...mainly for battery reasons*". This suggests that management of the laptop's battery and power states affects consumption but this will vary depending on the type of device, state of disrepair and the person using it.

This also appears to be the case for PCs. For example, we can see clear periods in the power data when Henry's PC was on and off—his PC switch-off is visible around 2 A.M. in figure 3. He reports, "*I'll turn it off properly... I'll turn the switch off at the wall sometimes. I turn my hard drives off at night because the light annoys me when I try to sleep.*" Gary, on the other hand, leaves his desktop on all of the time as its used for both work and as a media server, and this is evident in the lack of gaps in his sensor data.

Our participants used their laptops and PCs in a multitude of activities, including listening to music, watching TV and movies, communication, shopping, getting news, and doing work. Whilst some types of activities might be reflected in a particular pattern of use, it seems that hardly any activities are distinguishable from the data alone. For example, Henry uses his PC for work, study and entertainment. The data from Henry's room showed that his "computer" (which was in fact a number of different devices served by two wall sockets) was on for a distinct period of time which, when asked in the interview the next day, matched a time Henry said he was running a test-bed as part of a paid consultancy project. However, Henry also did some work of another of kind—looking up lecture notes for his course—earlier in the day. These two different activities were indistinguishable from the electricity (resource) data alone.

PCs and laptops are often used to carry out multiple simultaneous or overlapping activities. For example, work becomes interspersed with listening to music or social networking. One of Callum's mini-accounts gives an example of such a situation: "*I was browsing the Internet and doing work on my laptop and listening to music using my speakers and amp.*" The multi-purpose, multi-tasking nature of these devices presents a challenge in directly attributing electricity consumption data to any one particular activity. Other entertainment devices such as TVs are usually dedicated to the provision of a specific service, making it easier to connect the data traces that they provide to a particular activity.

Perhaps because of their ability to support all sorts of different activities, participants often referred to their laptops in particular as the device that they use most regularly and could not live without. In the case of Miranda, although she acknowledges that her laptop needs to be fixed, she is waiting for a time when she would "*be less devastated without it.*"

It appeared that those with especially high entertainment and IT resource-reliance usually possessed a number of devices linked together, including the PC. For example, Henry reports that "*I've got my hard drives, my router, my two monitors, my stereo and my desktop, that's all hooked together.*" Quite often, these devices were used simultaneously, as a system, in order to perform an activity like gaming or watching TV. In this case, the energy makes the most sense attributed to the broader service of entertainment, rather than to the individual devices involved in that service.

It was common for the participants to mention watching TV and movies, playing computer games, and listening to music with flatmates and friends. This can be a regular, routine occurrence: "*Everyone's normally in the kitchen about 5 or 6 and everyone watches* Friends *and there's* Scrubs *on at the same time so everybody watches that*" (Henry). Sometimes entertainment events are pre-arranged. For example, Ellie will "*have like movie nights in people's flats*", whereas other times they are unplanned: "*We spend a lot of time in each others rooms just talking and watching telly*" (Henry).

Participants reported watching TV and movies, and playing computer games, for a break from work, because they were bored or had nothing else to do. For Ellie, whether she watches TV shows or not "*depends like if my friends are doing something.*" For Ian it depends on the particular time of the year: "*Well like the next few weeks its gonna be, next term, yeah, there'll be a lot of TV and that because there's nothing to do. No lectures, no group work, just revising, and there's only so much revision you can do.*" Henry does not play computer games as frequently as he used to because he is busier than he used to be, but also because he has found other things to do: "*First year I used to play lots of games... because well I had a lot of time and I was probably less mature[...] But now if I'm not doing something I'm doing something else. I'm socialising or I've found other hobbies.*" Access also factors into the amount some of the Blue participants watch. Ellie describes how an online service allows her to watch her weekly TV shows and according to Ian, "*It's been a thing this year. We got a free download thing now so we watch a lot.*"

Opportunities for Change: Based on this detailed understanding of energy used to support entertainment and IT services, we suggest four potential avenues for reducing it. First, our findings confirm Chetty et al.'s observations, that some gains appear possible by improving the technical efficiency and power management regimes of laptops and PCs [2]. Second, many entertainment and IT devices appear to be left in standby when not in use. This instant availability sometimes seemed useful: some participants would keep documents or web-pages open for quick reference. Third, less time spent actively using entertainment services appears feasible. This already seems to vary at different times of the year and for some participants it appears to be a resort when there is nothing better to do. Fourth, it is most remarkable that consumption in this category was dominated by a small number of participants, who appeared to spend more time gaming, working with IT, and watching TV and movies, typically with linked complexes of specialised devices supporting these pursuits. It is perhaps best to consider these participants as connoisseurs of these services and the technologies that provide them, and perhaps look to working with the wider (sub)culture that shapes these tastes.

Sensing and Accounting: It is feasible to associate electricity consumption values with particular devices (e.g. after [5]). Where those devices are part of a constellation supporting a service, this is the level that would require sensing. Since IT devices have diverse and often simultaneous uses, it will remain difficult to associate computer consumption with particular activities—consequently it may be difficult to understand what the possibilities are for reductions. A crucial first step might be to log the activity of applications on the computer to aid with finer-grained accounting.

4.2 Lighting

Lighting is a service relied upon across indoor life. It accounts for 16%–29% of the total energy consumption (figure 1). The per-bedroom average lighting energy is comparable (table 2), but the lighting energy in communal areas (kitchen, corridor and showers) is significantly more variable. The communal area total was highest in Yellow (84.8 kWh), almost twice that of the lowest, Red (45.6 kWh). Our interview data illustrates a mix of conventions, expectations and actions around turning lights on and off.

Leah always leaves the lights on and acknowledges that "*I do mean it, I am conscious of it though but I don't really do anything about it.*" Likewise, Wendy acknowledges that, in her flat "*we have them on all the time constantly*". She notes that her flat are "*literally terrible, we have all, everything plugged in, all the lights on, run the water for ages [embarrassed laughter].*" Indeed, this account is consistent with table 2. However two participants left lights on for a reason that went beyond simple indifference. Miranda leaves the lights on in the shared corridor "*because I've turned it off before and [pause] people don't know where*

Table 2. A breakdown of the lighting consumption in each flat. The communal areas are homogeneous in layout, light fixtures and sensing, and the associated energy used for lighting can be directly compared. Lighting totals for the monitored bedrooms are shown, alongside the per-bedroom average. This table contains none of our assumed figures for unmonitored bedroom or toilet lights.

Flat	Estimated light energy (kWh)						Unmonitored rooms
	Grand total	Communal area lights				Bedroom total (Average)	
		Kitchen	Corridor	Shower+fan	Total		
Green	92.12	27.31	18.55	13.75	59.61	32.51 (10.83)	5
Blue	136.19	24.95	24.03	18.65	67.63	68.56 (8.57)	0
Red	92.58	19.47	15.56	10.59	45.62	46.96 (9.39)	2
Yellow	148.34	32.06	25.17	27.58	84.81	63.51 (10.59)	2

the switches are in the corridor so if they come and its dark, erm, I get moaned at so I usually leave that on." Ellie was not sure whether the corridor light could be turned off because at her previous university, they had to be left on due to safety regulations.

Most of the participants spoke about turning the lights off, at least in their bedrooms, when they were not in use. For Donna, Henry and Miranda, this was a habitual thing. For example, Miranda switches off the kitchen light when she leaves because "*just growing up, my mum used to say 'switch off and save' and so I just always have, just a habit I got into.*" Before he goes to bed at night, Henry turns off the communal lights in Green because "*otherwise [...] they're just on for no reason.*" Donna, on the other hand, is motivated by climate change issues. When asked if there was an environmental background to her switching the lights off, she replied "*Yeah, I think we should all help to slow down global warming even if we can't stop it.*"

Three of the participants turned the shower room lights off because, otherwise, "*[the noise of the extractor fan] comes through the wall and its really annoying*" (Donna). Jess turned the corridor lights off because the light shone underneath her bedroom door and prevented her from sleeping. For Wendy, and some of the Blue participants, annoyance was sometimes a factor in leaving the lights on: "*I well I don't really like the dark. [...] when I come out of my room its dark and I'm like arrr*" (Wendy).

Opportunities for Change: Each flat contained fifty-eight fluorescent light elements. One clear avenue for saving energy is to replace existing fixtures with lower power alternatives. Though as Wall and Crosbie caution, this is unlikely to be straightforward, due to perceived performance and aesthetic shortcomings [17]. Our study does reveal surprisingly significant energy attributable to lighting, especially in the communal areas at night: one tactic could be to fit motion-triggered lighting, or equip the corridor with a low-power night light.

Sensing and Accounting: It is difficult to attribute lighting consumption to a particular activity and, in fact, it may not even make sense to do so as lighting is a basic requirement for almost any activity outside daylight hours. The important information for accounting is the state of lighting (on/off), occupancy, and outdoor light intensity. However, this utilitarian view may not be sufficient: from testimony it was clear that lighting contributes to perceptions of both security in adjacent rooms and to safety in the corridors at night.

4.3 Cooking and Refrigeration

The domiciles in our study contained two fridges, two freezers and a cooker. Food-related energy was between 20%–39% of the flat total. On average, over half of this comes from energy directly consumed by the cooker, one third as a result of the fridge and freezer, and the rest is other kitchen appliances (i.e. kettles, microwaves, toasters and standalone grills)—cooking and refrigeration are clearly visible in figure 3.

The cookers in the flats had four hobs and a built-in grill and oven, enabling participants to boil, fry, grill and bake foods. We saw that the energy required to prepare a dish is a function of cooking time and technique, and this is closely related to the type of foods being cooked. For example, eggs require little energy to cook because they use a single cooker element for a short period of time, whereas frozen chips require the oven for much longer periods.

We observed different cooking methods in each flat: Red tended to boil foods regularly (36% of the time), whereas Green often fried foods (34% of the time). Our analyses show that the most efficient cooking method (in terms of energy per unit of pre-cooked food weight) is *heating* in a pan on the hob, and this is employed the least (8% of the time). Both *frying* and *boiling* were more frequent (26%)—frying is more efficient than boiling. *Grilling* and *baking* are the most energy intensive, and these were used 19% and 21% of the time, respectively. Some foods were cooked using more than one method, inviting comparison of the time and energy involved: e.g. when sausages were grilled (6.7 kWh/kg average over 7 sessions) they resulted in 5.6 times the energy of when they were fried (1.2 kWh/kg average over 12 cooking sessions). We also saw variability in the energy required to cook the same food using the same method: boiling 100g of pasta used from 0.2 kWh–0.75 kWh (compared across thirteen cooking sessions).

Food preparation as practised by our participants typically relied upon the service of refrigeration, although the energy attributable to refrigeration seems less directly affected by times or durations of use. The very minor variation for refrigeration in figure 2 could be a result of different thermostat settings, frequency of openings, refrigerator model, or states of repair (e.g. faulty door seals).

Opportunities for Change: We observed energy due to lengthy pre-heat times and cooker components left on accidentally after use (in one case lasting five hours and consuming 9.4 kWh). These were most impactful for the oven: in general, the oven and grill are energy-intensive components and changes to their roles in meal preparation could lead to significant reductions. For example, discouraging the use of these components for small quantities of food, and encouraging their use to cook multiple meal portions to share or to store and eat later. We

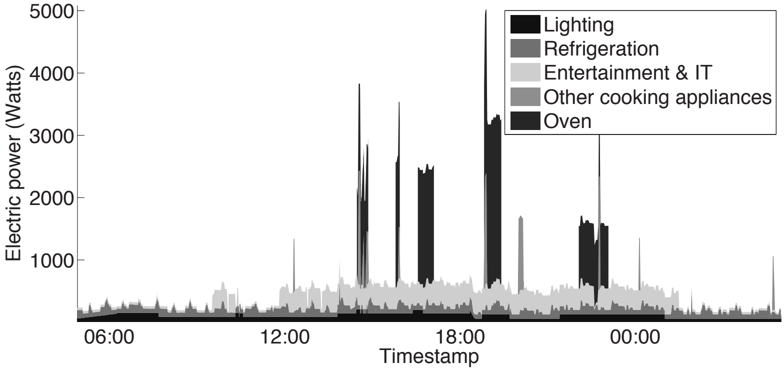

Fig. 3. A time-series representation of Green over the course of a day. Services are stacked on top of each other illustrating the relative proportions of each over time.

did see some evidence of this in our data, but in general participants preferred to be opportunistic with their food. When asked if they had regular or typical meal times, Jess replied "*erm, no not really*" and Polly said simply, "*I don't really have typical [pause] anything!*". A few of our interviewees, like Miranda, seem to perceive themselves as doing this sort of thing throughout the day: "*I just tend to eat when I'm hungry ...I just don't think about it. I just kind of graze, and I don't plan meals really.*" Fridges and freezers may help in efforts to optimise cooking energy through bulk cooking, and their energy is not impacted as dramatically by changes in use. Their presence may not be 'negotiable' but it may be possible to reduce the freezers from two per domicile to one, and the seals and settings should be checked as part of routine maintenance.

Sensing and Accounting: Energy data from the cooker may be best linked with data about the cook's technique—particularly, the settings, timing and cooker components used. Existing cookers should be monitored at the cooker's supply—even this resolution of data will present challenges in attribution (i.e. disaggregating cooker components used simultaneously), and leave gaps in understanding (i.e. identifying cooks and consumers of meals prepared). This is fertile ground for sustainable technological and social intervention [7]. To encourage social meals or increase bulk cooking, however, we should be careful not to neglect the importance of convenience—all eleven interviewees framed their daily cooking activities in terms of this.

5 Reflections on the Service-Oriented Approach

In our service-oriented approach, we have not only quantified the energies associated with entertainment and IT, lighting and food preparation, but also positioned them in their everyday context by providing an account of the actions, routines, infrastructures, devices, systems and expectations associated with those services. In discussing the three service areas, we have highlighted requirements and opportunities for pervasive sensor devices (summarised in table 3) appropriate to service-oriented accounting. For eco-feedback and other researchers striving for deeper and more nuanced understandings of resource and practice at home, we now provide a summary of the advantages and limitations of this service-oriented approach.

Table 3. Sensing considerations for service-oriented accounting

	Entertainment/IT	**Lighting**	**Cooking**	**Refrigeration**
Disaggregation scale	Per device where used independently; per complex where devices used in a system; within-appliance disaggregation to monitor particular states e.g. standby in combination with activity sensing	By light fitting, by room	By cooking devices e.g. microwave; Within-cooker elements e.g. grill, oven, hobs	By appliance
Time granularity	High—power consumption changes rapidly, these devices are actively used	Medium—to reliably capture on and off events at fairly coarse intervals	High (once in use)—to capture effects of cooking techniques & settings	Coarse—possibly only for a staged check
Sensors	Direct per-appliance	Luminance sensors directly on fixtures	Point sensor near or within-cooker; image-based possible but complex	Direct per-appliance
Activity sensing to enhance interpretation	Computer-based use logs to capture time spent actively using applications	Presence (motion); outdoor light intensity	Non-intrusive sensing of control settings	Door opened sensor
Possible framings	Organised around power states and complexes of devices; co-ordinated with particular uses of computers	Organised by room, highlighting consumption and significant unoccupied durations with lights on	Based on consumption of particular cooking sessions, and quantities of food cooked	Door-open durations may be matched up with consumption and amount of food in storage

5.1 Advantages over Resource-Centric Approaches

As Strengers and Pierce have argued, much of sustainability-related research has been concerned with estimation and display for feedback approaches. This has three tendencies: to limit the focus of enquiry to quantitative measurement of resources such as electricity and water; to cast “users” as rational resource managers [16]; and to cast designers as experts who decide what is sustainable and what is not [1]. Complementary to these arguments, we identify advantages that a service-oriented approach has to offer, over resource-centric approaches.

The infiltration of service-reliance across practice is made clear. Creating a comprehensive account of a single service shows how it is put to work in supporting multiple practices. In our study, IT was relied upon for personal and group entertainment, paid work, education and staying in touch with friends.

Lighting supported not only a majority of practices indoors, but also facilitated meaningful feelings such as cosiness or security.

Relevant systems of devices and constellations of services are easier to identify. In a similar way, the approach exposes interactions and dependencies among devices, and among services. Groups of devices (an amplifier, television and computer streaming video) worked together to deliver an entertainment service. The services of cooking and entertainment (watching *Friends*) were together relied upon to create a spontaneous (yet habitual) social event at mealtime.

Resource measurements can be actioned more effectively, taken in the context of everyday life. The relation of service provision to routines and meanings is just as important as the quantification of resources. At times, reliance on service can be very practical (leaving corridor lights on allows one to see when going to the toilet at night) and at other times, the service provision may not have immediate, practical utility but has important meaning (leaving corridor lights on gives a feeling of cosiness when in one's room). An energy-centric account might lead to the conclusion that motion-controlled lights are a solution to reduce lighting, but a service-oriented account could testify that corridor navigation and meaningful cosiness are both best supported by a nightlight. In the end, the problem space of "resource reduction at home" should not simply be one of the consumption of end appliances or taps, but should include the service-reliant practices, social meanings, expectations, and purposes of everyday life.

It facilitates a higher-level reconsideration of how service (and in turn, practice) might be reconfigured in the context of sustainability. Finally, a service-oriented approach more naturally lends itself to questioning the arrangement of everyday life, rather than simply "tweaking things" (resource management, appliance efficiency) within the domicile's existing, highly contingent regime of devices, infrastructures, and expectations. It allows researchers to more readily question the existing bounds of what is considered normal. Given the vast difference in energy observed for entertainment and IT in Blue and Yellow, should desktop computers, amplifiers, and large displays be somehow discouraged in student accommodation? This line of thought rapidly becomes politically-charged, wrapped up with concepts of need, expectation and entitlement. But arguably since practice is continually in flux, then researchers and designers might have as valid a claim as anyone to being active in its reshaping.

5.2 Possible Limitations of a Service-Oriented Analysis

Alongside the advantages, we should consider how a service-oriented approach might constrain understandings of everyday life, resources and sustainability.

Findings are highly localised and specific. Our service-oriented accounting is very much at the "micro" level, and transferability of findings must be approached with care. For example, our characterisation of entertainment and IT might be applicable elsewhere in the UK. Our findings on lighting in the specific context of shared student accommodation may be less widely applicable.

Service externalities are not accounted for. Focusing on service provision within the home tends to sideline or exclude resource and practice outside the home. For example, some of our participant accounts revealed that laptops were charged up and used to provide IT services in places like the library. Or, if we extend beyond energy to ask broader questions about the sustainability of services at home, then issues such as carbon impacts of appliance and infrastructure manufacturing and shipping, or energy generation, may be of concern.

5.3 Other Ways to Account for Services

While we do advocate investigative methods that lend themselves to a service-oriented analysis, we do not mean to mandate the methods used in our case study. We drew important elements such as agency, identity, activity, location and expectation from the discussion of sensor data during interviews with our participants, and the mini-accounts that they supplied. However, there may be other ways to gather such data. Pervasive sensing techniques such as activity recognition or positioning systems might aid in recording types of activity at the kitchen sink, or the use of portable devices around the house. Lifelogging (semi-automated capture of events, with the option for hand annotation) on a mobile phone might capture some of the same elements that our interviews did.

5.4 Specific Items for Future Work

As a final testimony to the merits of a service-oriented analysis, we would like to conclude by returning to some of our findings which exposed important areas for future work in sustainability at home.

Connoisseurs of IT. The high variability between participant bedrooms comes down to the amount of electronic equipment, and the durations for which it is active. We feel that this is a wider issue with entertainment and IT service provision: some homes have many more electronic goods, and those tend to function in groups (a video playback device might rely on a display and an audio amplifier). Why might it be a convention that lights be turned off, but desktop PCs be left on? The ubiquity of home and personal electronics is growing, but this seems to be rooted in rising expectations of the entertainment and IT services supported by those devices. Some of our participants relied upon large displays and personal media servers, on a daily basis. What are possible future alternatives?

Cooking and its relation to other services. In general, provision of different services was heavily intertwined. This was particularly striking with food preparation. We observed lengthy pasta boils and pre– and post-heating of the oven and grill, concurrent with socialising and watching TV in the kitchen, showering, and bedroom-based work and console gaming. Because certain types of cooking lend themselves to waiting periods, where no cooking-related action seems to be required, it appeared that the tendency of our participants was to simply go do something else instead. We would like to understand this interaction of services better in the context of our student participants (who emphasised convenience and flexibility when it came to food preparation), and it would be interesting to see how food preparation interacts with services in other types of household.

6 Conclusion

We have shown what new domicile-specific knowledges and insights may result from moving energy analysis to the level of *services*. In this demonstration, we have quantified the energy relied upon, and described how the service was structured in the context of everyday life (appliances, interactions, time-use, activity, expectation and role in practice). During the process, we have also put forth considerations for service-relevant sensing.

We expect that a service-oriented approach will require significantly more accounting effort than a resource-centric one. We argue that the payoff for this effort is a shifting from simple measures of how much energy is consumed by appliances, to a more inclusive understanding of the bundle of devices, infrastructures, practices, expectations and resources that make up a service. For researchers considering possible design avenues, it can immediately expose where services support single or multiple practices, what devices function in groups (and why), and results in a broader view of the possible reconfigurations of service. In contrast to energy-centric accounting where the design path tends to be one of managing resources more efficiently while maintaining existing expectations and arrangements, a service-oriented approach allows sustainability at home to be cast as a contingent yet still-negotiable interplay between resources, infrastructures and devices, and practices which have purpose and meaning.

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