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## Unpacking the resource impacts of digitally-mediated domestic practices using resource trace interviewing

Adrian Friday<sup>a</sup>, Mike Hazas<sup>b</sup>, Oliver Bates<sup>a</sup>, Janine Morley<sup>c</sup>, Carolynne Lord<sup>a</sup>, Kelly Widdicks<sup>a</sup>, Alexandra Gormally-Sutton<sup>d</sup> and Adrian Clear<sup>e</sup>

<sup>a</sup>School of Computing and Communications, Lancaster University, Lancaster, United Kingdom; <sup>b</sup>Department of Information Technology, Uppsala University, Uppsala, Sweden; <sup>c</sup>Sociology, Lancaster University, Lancaster, United Kingdom; <sup>d</sup>Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom; <sup>e</sup>Engineering & Informatics, National University of Ireland, Galway, Ireland

### ABSTRACT

The home has been the subject of investigation in the social sciences and interaction design communities for decades. This has been driven not least by a wish to understand technology, energy demand, and how it might be understood in terms of social practices. In this paper, we reflect on several studies that have sought to capture this relationship. We introduce an evolving methodological approach we term ‘Resource Trace Interviewing’ that extends interview practice using visualizations of fine-grained quantitative data from sensors and software deployed in the home. By facilitating fuller accounts and joint sense-making between participants and researchers, this method better reveals the patterns of technology and energy use in the digitally connected home, and how this in turn relates to domestic practices. We reflect, for the first time, on the strengths and limitations of this approach as a guide to others studying similar socio-technical settings.

### KEYWORDS

Mixed-methods; sustainability; energy demand; ICT; domestic practice

## 1. Introduction

The continued growth and significance of household energy demand (Cuce 2016) makes the home an important place to focus on demand reduction and contribute to addressing climate change. Complicating matters, the home is shaped by differing technologies, and the relationship these have with domestic practices (Shove 2003; Eon et al. 2019). These technologies are increasingly digital and connected, and have been linked with the growing environmental footprint of ICT—thought now to be between 2.1 % and 3.9% of global greenhouse gas emissions (Freitag et al. 2021).

One way to conceive of the home is as an intersection of different social practices (Hand, Shove, and Southerton 2007). This conceptualization emphasizes the importance of temporal patterns, and the need to unpack the dynamics and rhythms of households (Southerton 2006; Walker 2014) recognizing the ordering effect and significance of time (Zerubavel 1979; Durkheim and Swain 2008). Rather than being assembled from the conspicuous and unusual, energy demand usually results from the repetition of everyday ‘ordinary consumption’ (Gronow and Warde 2001; Shove and Chappells 2013), underpinned by the physical and technical infrastructure of the home. Reaching an

**CONTACT** Adrian Friday  [a.friday@lancaster.ac.uk](mailto:a.friday@lancaster.ac.uk)

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appreciation of this relationship between energy demand, and repeated performance of practice (which implicates the digital technologies of the home) is key to our understanding.

To unravel the knot of practice, technologies, and energy demand and how this relates to the performance of domestic practice has called for new methods of enquiry beyond ‘classic’ use of ethnographic observation and interviews with householders. This has included autoethnographic video-based home tours (Pink and Leder Mackley 2013) where householders record sites of importance to jointly discuss in later interviews, and other well known visual enquiry methods, such as photo elicitation (Harper 2002; Dillahunt et al. 2009), where photographs are used as a resource for discussion and to build relationships between interviewer and interviewee. With the increasing implication of digital technologies in practice, ‘interaction traces’ an actor-centred approach where traces of digital interactions with technology (Geiger and Ribes 2011), and its use to construct practices (Dubois and Ford 2015), has been suggested as leading to fuller accounts and allows for joint sense-making in interviews. The explicit introduction of sensors into the home (Wall and Crosbie 2009) or computer network logging (Kawsar and Brush 2013) goes beyond this still, effectively bringing the researcher closer to sites where energy demand is significant in informants’ homes. This allows for new ways of unobtrusively observing the life of the home, connecting it to its associated energy demand, and providing a useful way to quantify and analyse domestic practices to inform fuller sense-making and analysis.

Our work sits at this precise intersection of methods. We integrate explicit sources of quantitative data gathering, such as in-home sensors and traces of device interactions and their communications, which allows us to unobtrusively account for both intentional and unintentional interactions with technology in the home. We combine these with qualitative insights about the home as a system of practice (Eon et al.

2019) revealed through interview methods to help us understand performances of domestic practices as implicated in energy demand. As we have previously argued, combining insights from qualitative accounts with quantitative measures gathered from the home, is vital for raising the unit of analysis from merely energy levels, to the practices which drive these (Bates et al. 2012). This method also brings new materials to the interview process, in many cases leading to greater elicitation and fuller accounts of domestic practices than would otherwise emerge. We term our sensor and data augmented method of enquiry ‘Resource Trace Interviewing’.

In this paper, we reflect upon five studies where we have set out to explore this site of enquiry in various ways. We use each investigation as an exemplar whereby we explore the mix of quantitative and qualitative methods we deployed, and how these together bring out new insights. Core to our approach, is the exposition of everyday life as presented to participants in the form of graphs and visualizations of their home data and interactions in the home in order to further elicit accounts about the mundane and routine that might otherwise go unnoticed in typical interviews or diary studies. These data further allow us to quantify and discuss the relative energy or other impacts of these practices in interviews and analysis. Critically it also allows us to jointly seek explanations for the relationship between practice, technology and energy, which goes beyond the separable methods of enquiry.

Qualitative approaches to practice have been common in the literature (Southerton 2006; Gram-Hanssen 2007; Southerton 2013), yet quantification expands this: it allows us to see the ordering and temporal nature of practices and technology use—when they occur, how often, and how they are routinized and structured in time. It also allows us to attribute metrics and magnitudes relating to energy and environmental impact (e.g. electricity used, data demand, carbon footprint) uncovering the relative impact of different

performances of practice and inviting comparisons to be drawn between the energy intensity of these across different households. This brings a new ‘resource impact based’ perspective to understanding the significance of domestic practices.

Our contribution in this paper is to draw out the specific strengths of Resource Trace Interviewing, informed by the studies we have published over the past decade. We explain what understandings were brought forward by applying this method, which we believe important for stimulating and informing future similar studies. While our previous papers have offered analytical contributions to specific domains and contexts (e.g. cooking Clear et al. 2013a, achieving thermal comfort Clear et al. 2014), and others, none have claimed the specific approach as a contribution. We therefore offer here a broader perspective needed to describe how the method can be applied to study energy demand in varied domestic practices.

Recognising that the relationship between energy and practice is complex—transcending individuals, and their interactions with specific devices and appliances—we also acknowledge the challenges and limitations of our approach, to drive future methodological research.

## 2. Related work

Understanding drivers of domestic energy demand has long been a focus of research from a wide range of disciplines and perspectives. Both quantitative and qualitative methods have been applied, drawing on the epistemology and methods of these varying communities.

Early studies of energy use in the home—dating back to the oil crisis of 1970s—used ‘whole home’ electricity meter data to interrogate and influence energy demand in the ‘Twin River’ experiments cf. (Bittle, Valesano, and Thaler 1979). The home, here, was effectively conceptualized as a ‘closed box’ that could be influenced by various ‘eco-feedback signals’ like daily use, cost, or through

comparison with neighbouring households. The drivers and differences in household energy demand, however, remained unexplained. It has been claimed that making householders more aware of the energy implications of their actions promotes energy savings (Petersen et al. 2007), and there is a substantial body of work over the years exploring this (e.g. Wilhite and Ling 1995).

Framing of energy use as ‘householder choice’ rather than the result of ‘domestic practice’, and whether this type of feedback leads to lasting change has led to notable critiques in the last decade (DiSalvo, Sengers, and Brynjarsdóttir 2010; Brynjarsdóttir et al. 2012), and in some circles at least, is widely discredited (Hargreaves, Nye, and Burgess 2010; Strengers 2014). As (Gram-Hanssen 2010a) explains, householders’ energy use can not be explained as traditional economically rational choices. Such accounts miss ‘the daily domestic dynamics and routines involved in [practices like] preparing meals; cleaning the body, clothes, and homes; and making spaces and people comfortable’ (Strengers 2014, 24). Rather, calling for analysis of energy demand in terms of social practices.

A social practice is broadly understood as ‘a routinised type of behaviour which consists of several elements [...]: forms of bodily activities, forms of mental activities, “things” and their use, [and ...] understanding, know-how, states of emotion and motivational knowledge.’ (Reckwitz 2002, 249). These are ‘ordered across space and time’ (Shove and Walker 2014, 46), and feature as the ‘basic unit’ of enquiry in social practice approaches. ICTs act as a resource in many differing practices, and can—at times—decouple practices from time and space constraints—enabling ‘more densely packed’ energy-intensive lives (Røpke and Christensen 2012). As with energy (Shove and Walker 2014), data traffic ‘is not consumed in its own right, but rather for the services that it provides.’ (Morley, Widdicks, and Hazas 2018, 130), or—in other words—is an

outcome of social practices. For example, Gram-Hanssen (2007) uses this unit of analysis effectively to uncover how practices concerned with teenage cleanliness may trigger energy consumption and waste (Gram-Hanssen 2007).

We follow Southerton in considering the temporal organization of life in the home as a ‘sequenced sets of interrelated practices’ (Southerton 2006, 435). As he argues, rather than encouraging consumers to make more sustainable lifestyle choices, understanding habit and routine action in terms of ‘the observable patterns of action that result from the reproductive performances of stable practices’ (Southerton 2013, 342) is what is needed. Such an approach allows for an understanding of the recursive relationship between practices and their temporalities, technologies, energy demand and how they co-construct one another.

Methodologically, qualitative methods such as ethnographic observation and interview has been supplemented by using the capture of data relating to energy use as part of a method of enquiry. Firth et al.’s (2008) UK study used five-minutely measurements of appliances’ energy use to identify the contribution of household appliances to the overall energy demand of the home. This work led for calls for further ‘quantitative and qualitative studies’ to explain the extreme variability between households they observed in the quantitative data at this level. Similarly, Grunewald and Diakonova (2018) combined the qualitative and quantitative, asking participants to install electricity meter loggers, and to record their household activities via a digital app, to uncover whether certain activities demand more energy than others—leading to new perspectives surrounding the differences in the immediate and total energy demand of practices.

Turning to more visual inspired methods (Jupp 2006), Pink et al. sought to understand ‘how media are situated as part of the routine, habitual, tacit, normally unspoken sensitivities

of everyday life in the home’ (Pink et al. 2013, 678) via autoethnographic video-based methods where householders ‘record’ video in the home that is used as a resource for discussion in interviews. Similarly, photo elicitation (Harper 2002) bridges between the home and the researcher, Dillahunt et al. (2009) for example, draws on participants’ photographs of what was important to them as discussion prompts in their study of energy-use in low-income communities, pointing to the importance of stakeholders outside the home (e.g. landlords, other households, community members) in shaping agency concerning energy demand.

Diaries are often found in methods used to study the home. Pierce, Schiano, and Paulos (2010) for example, sought to build a picture of ‘normal’, ‘overuse’ and ‘energy conserving’ interactions with appliances, supplementing interviews with handwritten ‘usage log’ forms by each home appliance. They usefully identify energy-conserving interactions (e.g. cutting, trimming, switching, upgrading, and shifting) that could influence future home technology designs. However, this brings with it an obvious challenge: the ‘log’, was noted to have reduced the use of certain appliances as participants wanted to avoid completing the log, highlighting a trade-off between participant effort and completeness of information using this method.

Trace ethnography (Geiger and Ribes 2011) and trace interviewing (Dubois and Ford 2015) make use of logs of user interactions with ICT devices to enhance interview enquiry. The deployment of specific hardware or software to enhance observation of the home goes beyond this to ‘sense’ the home environment and the role of technology engagement more fully. For example, Kawsar and Brush (2013)’s study of home Internet and device use offers a nice example of how network traffic data loggers combined with interviews can shed the light on the drivers of network use and demand (Kawsar and Brush 2013).

Such ‘ubiquitous’ sensed data gathered from the home is an important resource for eliciting accounts and joint sense making in interviews with study participants. Costanza, Ramchurn, and Jennings (2012) deployed energy meters in the home to enable householders to interactively annotate and attribute visualizations of their energy use against ‘energy consuming activities’, which intuitively relate closely to several domestic practices (Costanza, Ramchurn, and Jennings 2012). This visualization of user engagement with a system or environment (often beyond the home) using mobile or situated sensors has been a feature in ubiquitous computing and interaction designs for some years. For example, to promote reflection and learning (Benford et al. 2004; Rogers et al. 2004). We extend this as a method of enquiry to studies of energy and resource use in the digitally connected home.

### 3. Approach to measuring and explaining resource use in the home

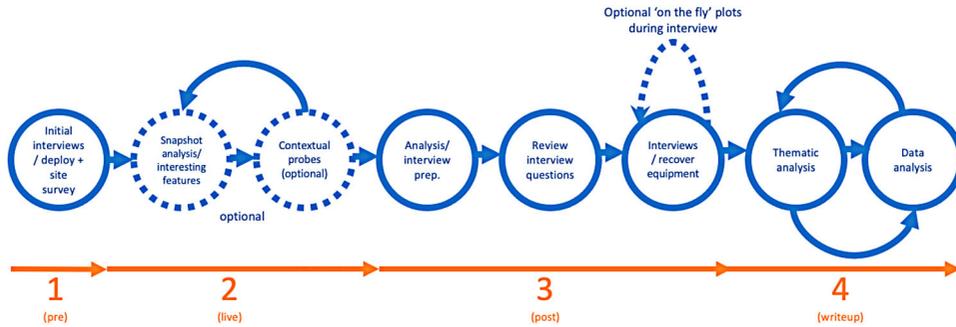
Resource Trace Interviewing brings the approaches from these diverse communities together. The method combines insights from a social theoretic perspective together with a technology informed ‘ubiquitous sensing’ approach that uses data from deployed sensors and data loggers to study a substantial period of home life. We have used it to study interaction with smart devices, tablets and computers; cookers and cooking; and home heating and thermal comfort.

Unlike previous visual interview techniques such as art based methods (Bagnoli 2009), and graphic elicitation (Crilly, Blackwell, and Clarkson 2006), which focus on the joint construction of the visual representation between interviewer and interviewee, we carefully select and composit graphics and data to use as a resource during interviews. As with Wall and Crosbie (2009)’s study of domestic lighting, ‘household energy consumption is determined by interactions between people and technology:

the combination of technology type and extent with level and pattern of use’ (Wall and Crosbie 2009, 1027), we take data relating to the participants’ interaction in the home into interviews to unpack the varied practices that constitute energy use. This leads to fuller and more revealing accounts about patterns of domestic practice, links and associates this with resource impacts (such as energy), and helps inform our analysis. The visual materials are just part of the overall approach, which otherwise is a more subtle dialectic between quantitative and qualitative, and how these methods compliment one another.

Our typical study process is illustrated in Figure 1. Installation of sensing software, hardware or any specialist logging devices happens at the start of the study. At this point we normally brief the participants and conduct any initial interviews with them. During the study we often monitor the system to ensure it is gathering data, and may look for interesting features to discuss later. At the end of the logging period, we prepare summaries and visualizations from the various data streams and logs to inform the questions and discussion during semi-structured interviews.

Table 1 summarizes how this combination of quantitative and qualitative methods has been mobilized in each of our studies: what we measured, and how this informed what we learnt. The first four studies explored domestic life in shared halls of residence on a University campus, which is a quite specific but also informative setting, enabling comparison between buildings of a similar construction and participant demographic. The last and most recent study reported here, focused on ICT device use and online connectivity related energy demand of households in the North West of England. Each study focuses on capturing the relationship between the observed practices and some resource use (electricity, heat, food, home appliances). The precise methods (what is logged and how) varies from study to study



**Figure 1.** Diagram representing the stages of data analysis and the overall process from initial deployment and interviews through to post-logging interviews and analysis.

as necessitated by the resource in question and where in the home this can be sited.

We, as others, have found that automatically recorded data alone, however, does not explain social practices—it is necessary to explore this with participants—particularly in probing for fuller explanations. Aside from the complexity of defining and potentially isolating practices *at all*, there is always a gap between what can be sensed: technically, ethically and conveniently, while observing the need for participant privacy. Logged data of this kind is rather a low level and the identity of individuals is normally inferred rather than explicitly known. The gap then *needs to be bridged* from this to the practitioners, motivations and explanations involved in charting practices in the home. This is especially the case in shared households where multiple practitioners and their practices are entangled.

In more detail, the rapid visualizations developed from snapshots of data for use in the post-deployment semi-structured interview design are essential. We find that questions framed around the data of participants is especially powerful for triggering recall and seeking explanations of the routines that constitute practices, technology use and energy demand (Gram-Hanssen 2010b; Southerton 2013). Figure 2 is one such example which integrates data from indoor and outdoor conditions, and user interactions with our system.

In our study of thermal comfort (Clear et al. 2014) we created two graphics for each participant interview: a graph of room temperature for a specific day of the study, and a bar chart of interactions with the heating system deployed. The first allowed us to talk together about the extent they felt able to make themselves comfortable, and the feeling of control they believed they had over this. Specific questions included ‘Is there anything about the graph that surprises or confuses you?’. Where observable trends were seen, participants were asked, ‘Does it generally feel warmer in the evenings and colder in the mornings and days?’—leading to a discussion of their routines, and how comfort was achieved in relation to these.

Using a second plot, we asked about reasons for interacting with the system, and any specific features we could see (e.g. interaction tailing off over time). For example, pointing to their graph we asked a participant: ‘On one particular weekend you interacted a bit more than the rest, can you remember why?’. These visualizations provide resources for discussing both the participant’s overall experience, but also potentially noteworthy events. Effectively, the graphs provide a shared frame of reference to scaffold conversation: the graphics serving as a prompt for recall and discussion, better contextualizing recollections and allowing us to ‘zoom in’ on specific days, time ranges or patterns—rather than relying just on the participants’ recall.

**Table 1.** Table summarizing five of our studies of energy use and practice in the home that have all utilized our mixed-methods approach.

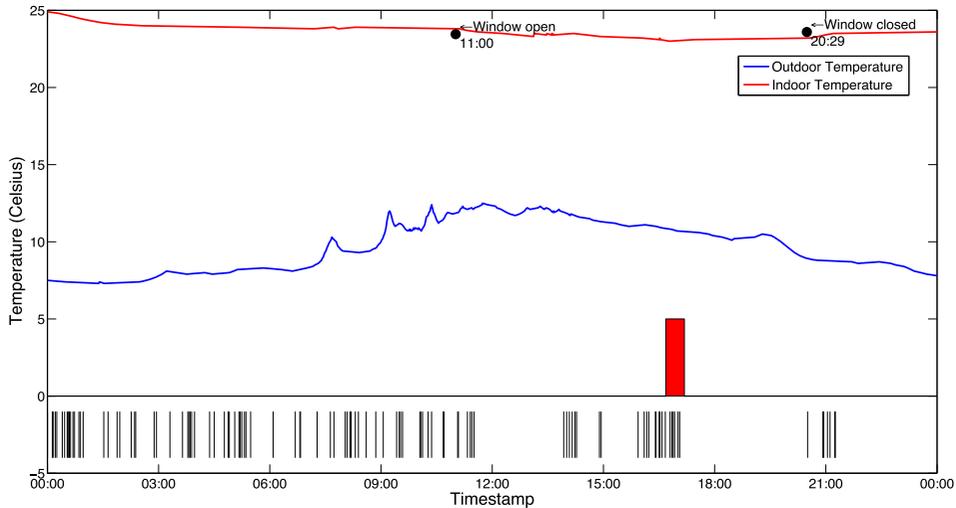
Goal	Supplementary data	Context	Research questions	Method	Findings	Further reading
Achieving thermal comfort	Diaries. Temperature, humidity, window and door opening.	Variations in ways of 'doing comfort' and consequences for energy demand	Attempt at comprehensive account of comfort in practice: to a more dedicated focus on clothing. How do ways of dressing vary between people? How do they vary for different spaces, purposes, activities? And with what consequences for energy demand?	Serial interviews. Diaries. Sensor data on temperature, humidity + window and door opening. Used in average form in analysis. Presented in later interviews, showing change over week and comparisons to other rooms to discuss correspondence with their experiences.	Variation in strategy taken; importance of experience with adapting comfort; significant energy implications of being more or less personally adaptive (19–76%)	(Morley and Hazas 2011)
Energy used by IT and media consumption	Per-socket electricity monitoring; whole flat electricity use	Variations in electricity-use attributable to variations in the practices of residents	How does electricity use vary with the practice of residents? What's the role of IT and media use have impact and support what people do?	Socket monitoring + interviews. Interviews consisting of account of daily routines, based on the previous day. Later use of graphed socket data for previous day, plus other interesting / confusing 'events' to (a) bring out more details on device-use within routines; (b) make better sense of monitor data.	How much variation there is in similar practice due to 'device eco-systems' (3.5–34%); the cumulative impact of long running and repeated use of lighting, cooking and refrigeration.	(Morley and Hazas 2011; Bates et al. 2012, 2014)
Cooking	Images of cooking; electrical energy used	Students in shared living accommodation	What do people cook and eat? What is the energy and GhG associated with their diets and cooking practices?	Automated photographic record of cooker use, used to (a) 'observe' and tabulate cooking activities by individual 'chefs' (b) as a basis for estimated energy use. Combined with (brief) interviews with some of the participants.	A convenient diet leads to a high cumulative impact even from relatively low GhG ingredients; diet change is more significant than changes in cooking method (embodied vs. direct);	(Clear et al. 2013a, 2013b)
Heating and comfort	Motion, light, humidity, temperature, door and window sensors	Students in shared living accommodation. Base phase followed by intervention phase. bedrooms where intervention was deployed.	What do people do to keep warm and cool? How did existing practices come to be? What are the things that influence existing practices (energy intensive or otherwise)? To what extent is there scope to change thermal comfort practices to be more sustainable?	Winter study. Sensing and qualitative accounts in a baseline phase to reveal practices and link them to an indoor climate. Motion, light, humidity, temperature, door and window sensors. Energy estimated through radiator flow. Intervention phase with different radiator control. Sensing and interaction (interface) logging. Discussion of graphical representations of	Strategies undertaken; engagement or not with drifting indoor temperature and 'adaptive boost'; remote vs. local control; personal adaptations (e.g. clothing); insights into barriers to adopting a more adaptive heating approach	(Clear et al. 2013a, 2013b, 2014)

Data demand	Network router traffic flow logging; per-media appliance energy logging; or logging on the mobile device	Smart phones; tablets, game consoles, TVs (data traffic related energy demand)	What contexts do people use their devices in the home? How does this practice vary in energy intensity? What contexts and practices drive data demand?	Logging of wireless network (router). Attribution of top consuming 397 network services (to listening, watching, gaming). Pre-interview to discuss media and IT use; post-logging to discuss specific usage patterns.	Time of use: top consuming services (video; YouTube); the rise of 'multi-watching' (more devices, more demand); media-multitasking. Time filling with media.	(Lord et al. 2015; Widdicks et al. 2017, 2019)
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Figure 3 is an example of a visualization used in a participant interview. In this case, of energy demand in a participant's individual study bedroom. Notably, these charts uncover the 'typically mundane' and often repeated activities that make up the bulk of domestic energy demand—yet might otherwise be unremarkable to participants due to their very regularity and ordinariness. Here, the blue traces depict the presence of background 'always on' devices whilst the green demonstrate the 'peaks' that relate to the use of the computer, game console and other connected media devices. Meanwhile, the 'area under the curve' represents the energy associated with the practice for this day. Joint discussion or 'sense making' of this has helped us find a shared explanation of the context, rationale or identity of those involved—not visible from the logged data alone. The distinction between ongoing energy use 'in the background' as a scaffold for domestic practices, versus that more closely linked to direct or specific user interaction, is an important one in terms of understanding energy demand and base load in the home.

In most cases, the joint exploration of these data reveals 'surprises' or anomalies where peaks in demand need joint work to arrive at an explanation. For one of our participants, there were a large number of photographs of grandchildren. 'Cloud syncing' of the photo albums on the grandparents' devices was clearly a significant driver of data demand each Tuesday. This is just one example, but our point is that in almost all cases, we learn more in the interviews as a result of integrating these data into the interview process.

In truth, while this is the core of the approach, the precise arrangement of the methods is more nuanced. There is a dialectic between the quantitative and the qualitative, where each may inform the other and be used in various permutations. For example, preliminary interviews may lead to targeted deployment of sensors or data loggers, whose data is then used to shape interview strategies to elicit



**Figure 2.** A single day in one of the flats in the thermal comfort study. Blue is the outside temperature. Red is the substantially higher and more consistent indoor temperature. Motion detection is shown as the lower black vertical bars. The window open/close events are labelled. The relatively slight effect of having the window open or closed while the heating remained on can be seen in the red trace. The red rectangle is interaction (heating) triggered by the inhabitant.

accounts. In combination these data inform the analysis and theme development, which may again be shaped or parameterized by the combination of methods. We have used data from a large study to inform which participants we choose to focus upon. For example, we might choose whom to interview based on their comparative energy demand. Or we might choose study participants with particularly energy intensive media and IT-related practices (Bates et al. 2012; Widdicks et al. 2019). We have even, less commonly, used live data to send ‘contextual probes’ (Morley and Hazas 2011), that is, simple questions to participants that ask for brief comments about interesting features in their data.

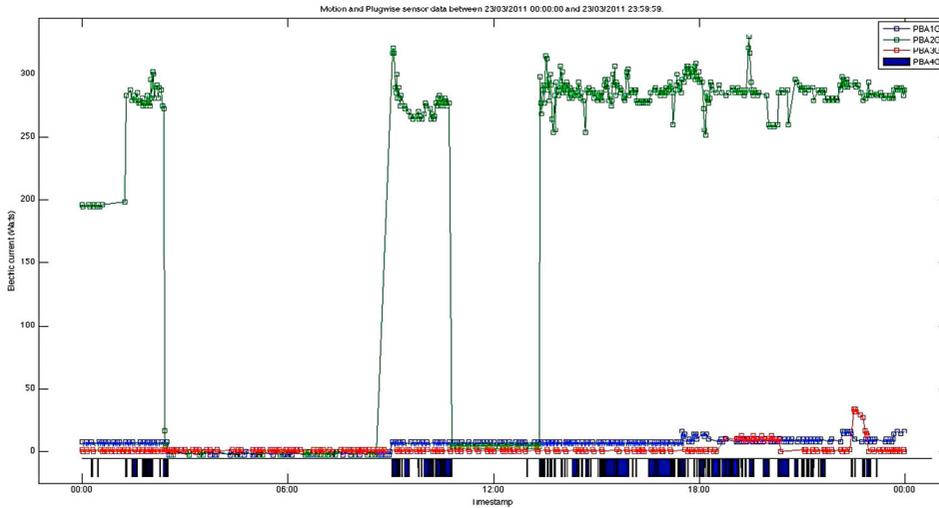
Finally, these data can itself be thematically coded, or inform the codes used for thematic analysis (Braun and Clarke 2006). For example, after discovering the significance of online streamed music as an important class of network traffic (linked in turn to significant energy demand) (Widdicks et al. 2019) we then coded thematically for ‘listening’, rather

than developing themes from the interview transcripts alone.

We find the quantitative data valuable to augment the reporting of our findings by providing magnitudes or ranges of resource impact relating to domestic practice as it varies between participants and households, and so on. We have used this to estimate the possible scope and impact of changes to performance of domestic practices, to weight our recommendations and conclusions of where to focus in future work. To make this clearer, we now illustrate this range of uses of the approach by drawing on exemplars from our past work, below.

#### 4. Resource use implicated in domestic practice

Resource Trace Interviewing allows us to get to nuances and variations in how technologies in the home are used to perform domestic practices, and the energy or resource demands associated with this. We now look at some of



**Figure 3.** Socket electricity data for one day in a participant's room. Green = Computer, Stereo, 2 monitors, laptop, games console; Blue = 2 Hard Drives, Wi-Fi router; Red = unknown. Dark blue bars along bottom indicate when motion was detected. First published in Morley (2014).

the insights arising in a number of our previous studies.

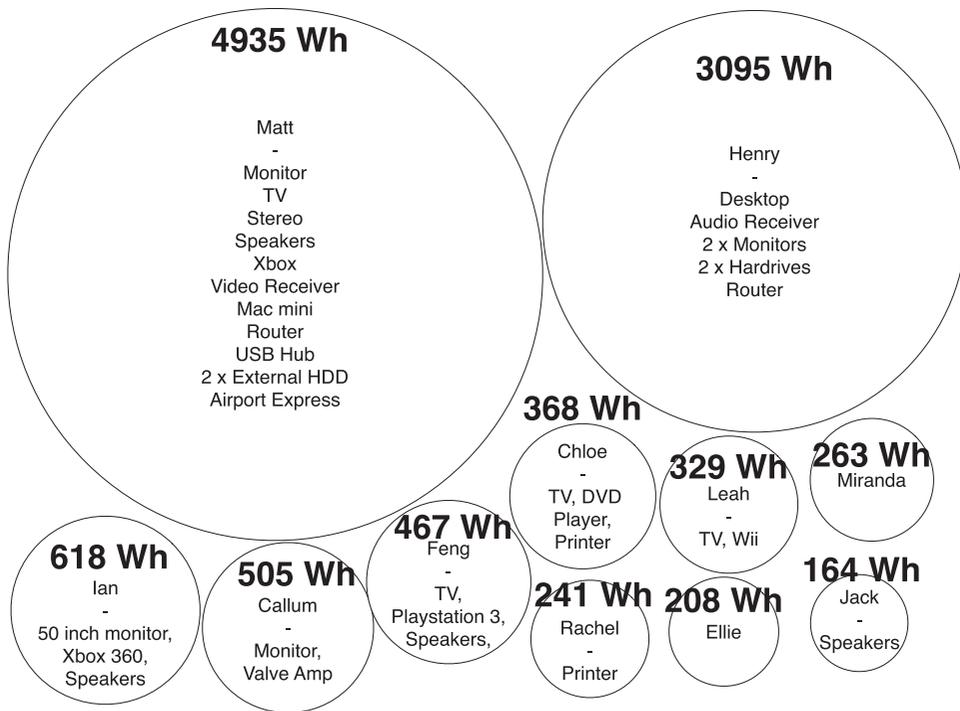
#### 4.1. Unpacking ICT use in the connected home

ICT devices in the home support and are intermixed with many domestic practices, as also observed by (Pink and Leder Mackley 2013). The intermixing of roles these devices play, presents a particular challenge in relating energy consumption to a specific domestic practice.

We found in our study of student residences unsurprisingly that all our study participants owned a laptop and used them regularly to support a mix of practices relating to work, entertainment and connection with their friends and family (Bates et al. 2014). Laptops supported studying courses (writing and accessing materials) and communication (most participants mentioned social media, or communicating with friends and family). But this is not all that laptops 'did': they were many things to their owners: participants depended on laptops for music, TV and film watching, shopping, and keeping up-to-date with news.

From our combined study data we noted that the most energy demanding laptop we measured used double the daily direct energy of the least demanding. However, overall this was far from the most significant part of that owner's total energy use, since laptops are relatively low power devices compared with other household appliances. The quantification of energy use exposed both this variation in demand, but also put this in perspective with other, more impactful, technologies and practices in the home.

Adding further complexity to our analysis, we found that laptops were frequently plugged into multi-way extension cords with other devices. They were also often linked by cables and networks to other devices that were frequently used at the same time. This presents analytical challenges in isolating the laptop's use from the other devices. But also highlighted the important relationship between devices in the connected home as a 'wider constellation' of devices could enable a certain practice or other with varying degrees of experience and fidelity. Games consoles and external peripherals were also similarly linked in these ways.



**Figure 4.** The average daily consumption of 11 participants' devices, showing the variation in personal inventory and its associated direct energy consumption. Laptops and mobile phones are not listed, as all participants had one of each. Reproduced from Bates (2015). Note we have retained the pseudonymous identifiers used in the published thesis.

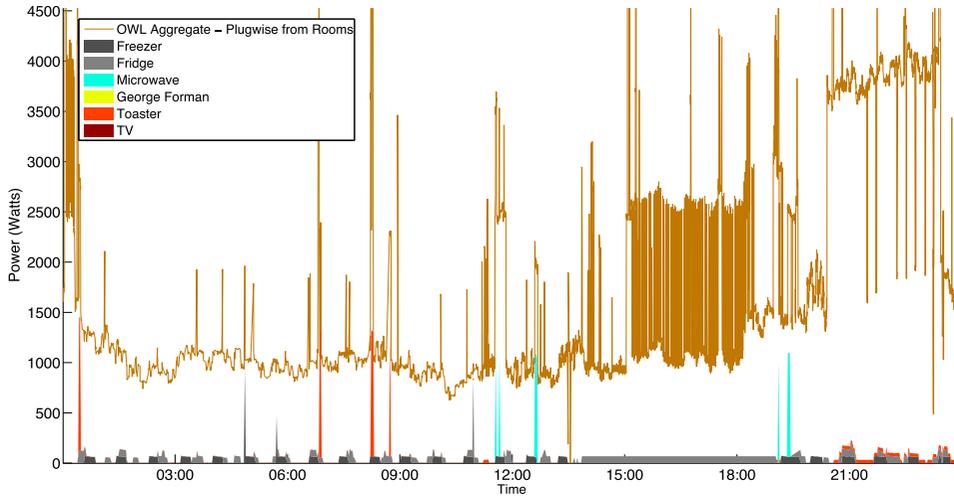
Some sex-based differences became obvious: most female interviewees did not use more than a couple of other electrical items in their rooms (e.g. phone charger, hair care related appliances). Whereas some of our male participants had assembled these more complex 'constellations' of devices to support entertainment and work—for example, driven by the wish for a 'high-fidelity experience'—with significantly higher associated energy demand. This is illustrated by Figure 4.

To cut through this intermixed and interdependent set of domestic practice, interviews have proven essential. Not only do devices become enmeshed across several practices, but the practices themselves become intermingled: for example, work becomes interspersed with looking at videos and the checking of social media. Participant accounts were helpful in teasing these apart and helping

explain the observed differences in related network use and energy consumption.

#### **4.2. Foregrounding unremarkable and autonomous resource use**

Some activities are sufficiently routine that they are not particularly memorable, but this doesn't mean they aren't important in understanding resource use in the home. Similarly, many devices use energy even when not in 'active' use by householders. The cooker is one such example. Cooking is a significant user of energy in the homes we studied. Yet, cooking is itself often routine and—potentially—less memorable due to its regularity and background nature. In our study of cooking (Clear et al. 2013a) we were able to look for interesting features to discuss—such as periods of conspicuously high energy demand;



**Figure 5.** Appliances in the kitchen with whole flat trace (includes the cooker) for one flat on 13th March 2011 with all bedroom appliances subtracted. The hobcam reveals ironing at 12 pm, the oven at 1 pm for 40 min (the spikes are the hob), and three hours of cooker use from 8 pm—the hob, cycling before 9 pm, grill at 10 pm and over from 10.30 to 11 pm.

oddly timed meals outside ‘the normal’ societal temporal locations (Warde et al. 2007); and surprisingly long cooking sessions. By linking these data with timestamped photos of the cooker, we were able to reveal more detail on the meals in question, and the shared and individual practices of the householders.

Figure 5 shows the overall flat power consumption (brown trace) including cooking appliances and other devices that make up the base load of the flat. Note how there is a significant ‘gap’ between this and the aggregate of the other kitchen appliances during cooking events (midnight, 4 pm, 9 pm). It also shows the times at which food practices occurred, and when combined with interviews, the role of shared and individual cooking in overall composition of energy demand in the flat.

A vivid picture of life in the flat kitchen emerges: the day started early with breakfast around 6 am (when one participant got up for rowing). Photos showed that breakfast often consisted of grilled sausages, though unconventional options could include reheated kebab, Chicken Kiev and chips, and noodles and broth. Longer cooking events (over 1 h) were

most commonly explained by more than one person sharing the cooker and overlaps in meal preparation. The occupants of this flat often ate together between 3 and 5 pm. Some foods were left to cook slowly over extended periods (1 h or more), even on the cooker top (hob) on occasion—sometimes these were foods that could, theoretically, be prepared in 10 min or less, with less energy footprint. Practices within each flat varied widely, with different temporality, and associated direct and embodied energies; inviting useful comparisons.

It was the explicit combination of data, visualization of these data and, in this case, motion triggered photography, that unpicked the energy supporting ordinary life. Interviews alone would struggle to reveal the details of how participants prepared their food, especially unconventionally (e.g. late night toasting of marshmallows!) (Figure 6).

### 4.3. Exposing variation in demand

Seeking to understand ‘the unique influence of occupants upon variation, specifically relating to the way they inhabit a home’ (Morley and



**Figure 6.** On a Monday evening, marshmallows roasting on an open hob.

Hazas 2011, 2041), we re-examined the data collected from student flats in (Bates et al. 2012) with a focus on the variation in the energy intensity of similar practice performances.

Daily energy demand did vary considerably between apartments, even in the same residential block where the construction and infrastructure is similar. Figure 7 shows the day-to-day variation for four apartments over the course of the monitoring period. Marked and sustained differences emerged in the mean energy demand of each flat, but their relative level of consumption was stable with respect to one another throughout. On closer inspection, the lowest consumption seen (a regular trough) occurs each weekend, suggesting a relatively familiar household pattern of demand.

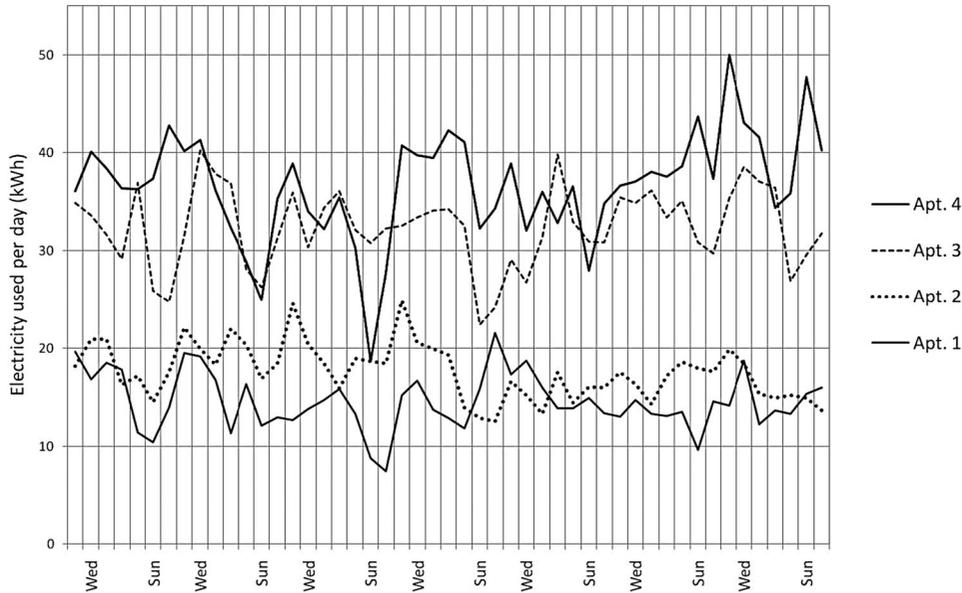
In this study, the quantitative data was used in several ways including allowing us to send quick informal questions by text message as a lightweight form of ‘contextual enquiry’. We used these data in selecting whom to interview and for joint sense making in interviews. Halfway through the monitoring period we chose interviewees from high and low energy demanding

flats: our aim was to deliberately explore whether practice variations could account for the differences in energy consumption. Combining narrative accounts with direct measures of energy use highlighted effectively the variation in demand of domestic practices (Figure 4).

While we did find that the way occupants inhabit their apartments is a significant source of variation in energy demand, the degree of variability was not the same in all three sets of buildings: the more recently constructed blocks were less variable when compared with the older blocks. A factor of 1.5–2 versus nearly a factor of 3 in the older blocks. This suggests that while occupant practice was important, the building infrastructure and age and choice of large appliances is likely significant in explaining further variation.

#### **4.4. Energy beyond the digitally connected home**

Smart homes, and other smart environments, require that we start to consider impacts



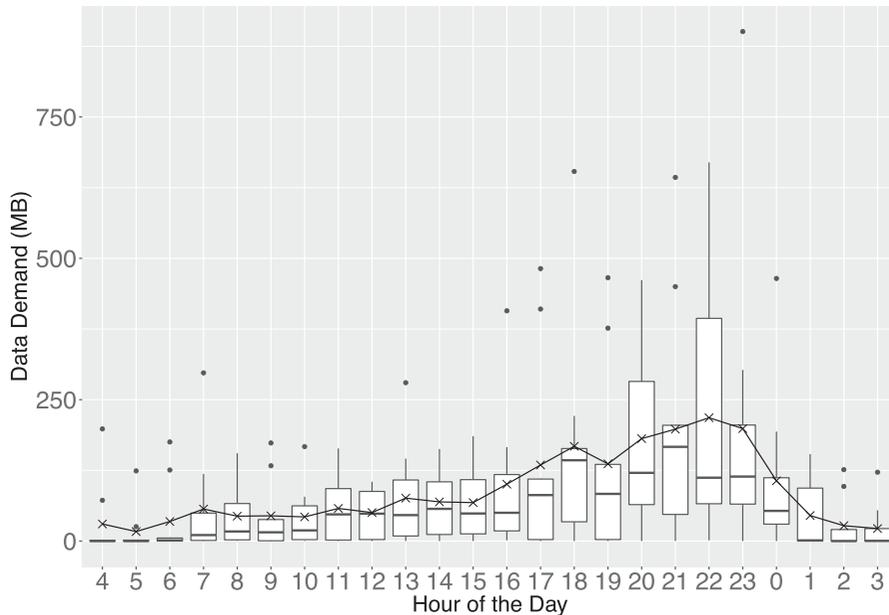
**Figure 7.** Daily electricity consumption profile for four apartments in one of the blocks selected for the qualitative study, reproduced from (Morley and Hazas 2011, 2042).

beyond the limits of the home, such as the Internet systems and services that enable many domestic practices. Smart appliances also exhibit their own autonomous behaviours that link to energy demand both inside and outside the home, e.g. cycles of automatic updates and downloads.

Online streaming, for instance, is noted to take a significant proportion of our global online consumption (72% of consumer traffic in 2017) and has an expected Compound Annual Growth Rate (CAGR) of 34% for 2017–2022 (Cisco 2019, Table 15). Drawing on estimates of the energy and carbon intensity of Internet services, we have used our approach to look at the most energy-intensive digital mediated practices in the home more holistically—estimating both the energy use in the home and in the supporting infrastructure (Widdicks et al. 2019). Exploring this interrelation of home and Internet services, allowed us to question changing trends in ICT use and their impacts on energy demand over time. For instance, whether online streaming has, as is

sometimes claimed, ‘replaced’ the use of the more energy consuming family TV, or is instead ‘layered on’ as an additional energy demand.

To record Internet use, we added a specially configured network router to each household to timestamp each connection to an Internet service (not the data payload) for one month. We recorded the source and destination Internet Protocol addresses, the number of bytes transferred in each direction, and mapped these addresses to the human readable names (DNS records). These names and IP addresses helped us identify the corresponding appliances and connected devices inside the home. We manually categorized the most data (and therefore energy) consuming top 90% of Internet services: corresponding to 357 high level Internet services from over 20,000 domains in total. We then mapped these domain names to Internet services and categorized these further into participant practices. While—in principle—this mapping could be partially automated, this is complicated due to the



**Figure 8.** The average hourly data demand for watching for all households (Widdicks et al. 2019). The overlaid line and crosses represent the mean; the dots represent the outliers. The figure is supported by 9 months of fine-grained network logs. Some samples lie outside the inter-quartile range because data demand is non-normally distributed.

structuring of Internet services into data centres and content distribution networks, and also how an Internet service may relate to several, possibly interacting, devices in the home. For example, ‘pc-nowtv-ak.vod.sky.com’ was mapped to the video streaming service ‘Now TV’ which we further categorized as ‘Watching’. To make further sense of how this integrated into the lives of our participants, as before, data visualizations were used in the post logging period interviews. This was insightful for understanding services less commonly known to the researchers as well as those which had not been previously mentioned by participants. Participants also helped us separate demand relating to intentional use from ‘automated’ data demand (e.g. adverts).

Numerically, this categorization uncovered practices that were the most data demanding, allowing us to calculate the relative magnitude of different services, the times of day this

occurred, and the devices involved (Figure 8). Here, median data demand in the evening, and films into the late evening comprised the most intensive ‘watching’. More unexpectedly, we found the relative importance of ‘listening’ to streaming audio services. Plus the otherwise largely invisible but substantial and growing ‘system updates’ (downloads) to games consoles and other networked home appliances. In our sample, YouTube streaming dominated other services, comprising nearly 50% of the streaming related data traffic.

#### 4.5. The relative importance of changing practices

The quantification of the energy impact associated with domestic practices, has helped us estimate the potential significance if high consumers were to follow the path of the lower consuming ones. This table taken from Clear et al. (2013a, Table 2), reproduced here as

**Table 2.** Each household's daily watching demand, the number of days spent watching, and their top services (see Widdicks et al. 2019).

H #	Avg. Daily MB	No. of Days	Top Watching Services (Avg. Daily MB, No. of Days)
H1	892	55	YouTube (803, 55), ITV Hub (184, 8), Akamai (128, 8)
H2	5	31	Facebook Videos (7, 17), YouTube (0.8, 26), Brightcove (2, 8)
H3	1287	36	Warner Bros UltraViolet (1962, 6), YouTube (310, 32), Watching Device Unknown IPs (964, 10)
H4	17	29	Brightcove (19, 10), YouTube (6, 28), BBC iPlayer (7, 11)
H5	2272	29	Now TV (3589, 13), Netflix (1658, 8), Facebook Videos (176, 27)
H6	5145	28	YouTube (4882, 28), Facebook Videos (79, 28), Sky Sports (2120, 1)
H7	1690	32	Sky (1472, 32), YouTube (286, 24), Facebook Videos (10, 5)
H8	2749	27	TV Player (2480, 17), All 4 (747, 15), ITV Hub (421, 14)
H9	5738	24	YouTube (3370, 24), Netflix (2285, 16), Twitch (910, 15)

Table 3, illustrates a range of possible household adaptations and how significant these might be in terms of the percentage of energy demand we explained.

Such approximations are useful for engaging participants in comparative dialogues about what they find normal, and whether such shifts could be possible for them. For example, we can compare the energy implications of a strategy such as optimizing cooking time versus adopting a less energy intensive diet. Naturally, participants often perceive value in the ways in which they conduct their activities (Bates et al. 2014). ‘Watching’ on a large TV with a high fidelity sound system, compared to ostensibly ‘the same experience’ on a laptop screen and speakers, by way of contrast. Lowering demand is rarely as simple as addressing any ‘lack of awareness’ of the energy implications of current practices (Strengers 2014).

## 5. Discussion

### 5.1. Reflections

When we started our studies of the home as a site of energy demand a little over a decade ago, we were motivated by what we perceived as a methodological disconnect between quantitative and qualitative approaches to such studies. The former, taking statistical or behavioural approaches (so called eco-feedback) to deconstruct factors that might explain variation or influence (lower) demand; and arguably struggling to do so. The latter, explaining

at a more socio-theoretical level the meanings, competences and social manifestation of energy and technology use, and how this continues to change the home. We were strongly influenced by attempts to broaden design—and human factors—led communities’ thinking about overly limited framing of sustainability and sustainable design (Brynjarsdóttir et al. 2012; Strengers 2014); and wanted to bring these two appreciations of metrics and practice-based framings of energy demand together.

The connected and increasingly digital nature of the home calls for methods that consider how technology supports the performance of domestic practices, and thereby links to energy demand. Whilst interviews allow a dialogue with participants to better understand and explore their experiences, these are to some extent limited to salient reflections and observations, and are subject to recall ability; problematic especially in longer running studies. Diaries and similar methods can help address this gap, but again, are not always consistently completed, and are intrusive in the longer term. Diaries and recollections typically do not capture, either, the mundane or background activity of the devices and appliances that are increasingly ‘on’ and consuming energy in autonomous ways. Ethnographic and observational methods are—of course—important for examining cultural and social settings, but also suffer from limitations of what can be observed, from where, and for how long; limiting the length of studies and number of sites of

**Table 3.** Summary of interventions proposed in Clear et al. (2013a).

Approach	Intervention	Rationale from findings	Indication of impacts targetted, from findings (ratio of total)
Modify the appliance	Audible reminders, auto shut-off	There was long pre- and post-heating of cooking elements.	<2% cooking energy (0.4%)
	Sensor-enhanced auto-cook function	Even amongst comparable dishes, there was a high variance in cooking durations and energy.	11% of cooking energy (2.4%)
	Replace/remove the most energy-intensive cooking technologies; for example swap the large ovens and grills with small toaster ovens.	Certain elements are particularly intensive, requiring a lot more energy to cook a similar amount of food.	Cooking energy due to ovens and grills was 16.9% (3.7%)
	In-cooker energy feedback display (elapsed time, running totals, per-element, historical)	The cooking length and method used to prepare foods influences the energy required, yet there was no evidence of participant awareness of energy required for cooking.	Potentially all cooking energy (21.6%)
Support communal purchasing and cooking	Social networking portals and apps to raise awareness of other people's shopping times and mealtimes, supporting coordination of shared meals in advance and in-the-moment joins	89% of cooking sessions contained a single cook, usually preparing one portion. When participants cooked in bulk for themselves or a group, it took less energy per unit weight. Participants enjoyed the social aspects of eating together and occasionally planned social 'proper' meals. But, ability to cook in bulk and share were strongly affected by limits on what was in the cupboard; by academic and employment timetables; and by a desire to be flexible or spontaneous.	All single-cook cooking energy. (14.1%)
	Digital assistants to support food shopping and cooking for a group. Putting together a collective 'what's in our cupboards' for a group.		
	Enable housing allocations based on preferences for types of food and meal times.	Despite the good potential for sustainable sharing of meals in these flats of eight, participants who lived together would most often eat different things, at different times.	
Change the food habitually eaten	Detect and log what food is purchased or prepared. Generate periodic reports on greenhouse impacts. Provide tailored advice on alternatives.	No evidence of participant awareness of food's embodied greenhouse gas impacts; diet has large influence on overall GhG externality; embodied emissions greater than direct by factor of 3.8. Certain habitual foods (jarred sauce, chicken, sausages, bacon, and cheese) had a disproportionately high embodied emissions (40%). Certain less frequent foods (steak and mince beef) had extremely high embodied emissions (14.8%).	Embodied emissions of high-impact foods was 54.8% (43%)
	Sustainable recipe books, online resources, and recipe generation	Diet has large influence on overall GhG externality; repetition of narrow range of meals; more engagement with food during 'proper' meals. Discovery and awareness of alternatives (through friends or online resources) can promote changes in diet and method of food preparation. Some people showed a willingness to experiment with new recipes and foods.	Potentially all embodied emissions (78.4%)

Notes: We describe (rightmost column) the portion of direct energy or embodied emissions which might be affected, as seen in the findings from our study. Note that we provide this as an indication of the scope of an intervention; the reduction that an intervention achieves will be less, and depends on its design, and the cooking practices in a given domain.

inquiry. Elements of the digital world are also hidden from these kinds of observational approaches.

Resource Trace Interviewing (illustrated in Figure 9) addresses this, and offers a detailed insight into specific homes' energy demand, greenhouse gas impacts and the use of connected technology within it. By instrumenting the home, and specifically energy demanding devices and appliances, we are able to capture interacting domestic practices as performed by the household, whilst looking at the layers of IT and digital technology found in such homes. This highlights, in an admittedly imperfect way, the role of these technologies in supporting practices, doings and routines. As with auto-ethnographic methods and diary studies, these data provide a resource to frame discussion with participants, highlighting both the role of the mundane and the exceptional in composing energy demand. It naturally lends itself to unpicking the growing role of the technologies in the home, the adoption of digital and connected devices, and how energy demand is constituted by the adoption and appropriation of these. We have found that networks and assemblages of devices are exploited to support particular practices (Figure 4). We also find, as might be expected, significant variation in how these technologies are linked to the meaning, expectations and competences of the individuals. We have shown how we can reveal the growing energy impacts of technologies, and shine a light on how differences in domestic practices, in turn, lead to diverse (often by some orders of magnitude) differences in energy demand or greenhouse gas emissions due to the specially curated ways in which technologies are assembled, used and made meaningful by our participants (Morley and Hazas 2011; Bates et al. 2014).

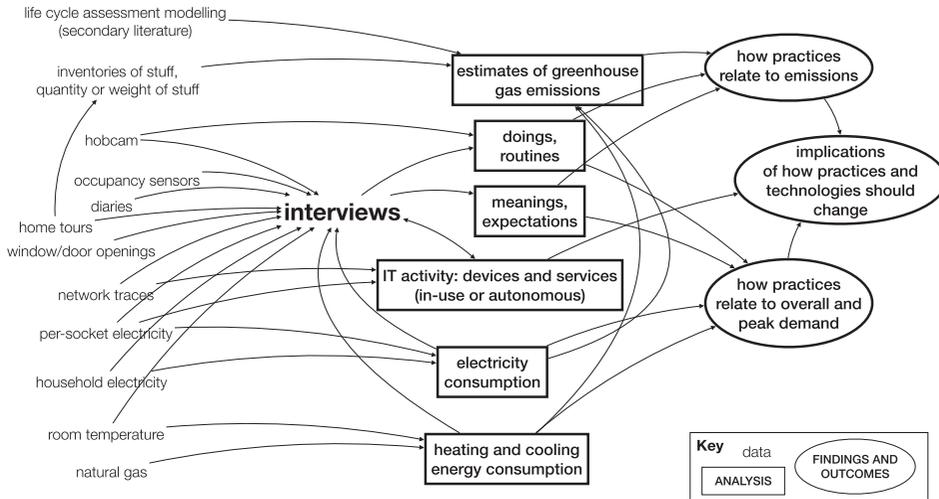
## 5.2. Lessons and limitations

As with any method, there are of course limitations: what can be sensed, the practicalities of

sensing and in interpreting the results in absolute terms and for different audiences. The data typically comes from multiple points throughout the home with a high degree of temporal resolution. This is an 'embarrassment of riches', with often more data than can be conveniently handled and categorized if appropriate constraints are not applied. We need to take particular samples of data and use computational tools and hand crafted software to help us analyse it effectively.

These data have the potential to provide insight into the household dynamics, and the temporal locatedness of social practices (Zerubavel 1979; Southerton 2013). Whilst we can accurately reveal when appliances are used, how much energy is drawn in use and in standby, this is not the whole story. It is often helpful to link back to the individual using the appliance, and beyond this, attribute the associated energy demand to the practices concerned. This is complex, not least due to the somewhat open questions as to what constitutes and bounds a domestic or social practice, in any case. There is a limit to what degree this can be known, although we can somewhat infer the individual and intention through what we know about the device locations and the relationship between things, space and people as we get to know our participants. The initial inventory and semi-structured interviews are particularly important to make sense of what we can see quantitatively—this is both the strength of the combination of methods in eliciting accounts, but also a limitation. Aside from eliciting accounts, the approach can bring a new appreciation for the involvement of digital connected devices in the home, their relation to domestic practices, and how this manifests in households and in energy use.

What can be measured is limited, and there is a need to be sensitive in participants' homes. How many sensors we can deploy, financially afford, the characteristics and accuracy of these, and where we want and are permitted to put them are all relevant questions and an



**Figure 9.** Summary of input data we draw upon, analysis, and outcomes collectively in our studies made possible by combining quantitative data from the home and qualitative methods.

important site of compromise endemic to the study design. The snapshot of data is, as with any study, something of an artefact of the duration of the study, and how it overlaps with the rhythm of the observed practices. It's important to recognize this limited view in interpreting these data, rather than risk over-interpretation. For example, in Bates et al. (2012) the study took place during cooler winter months and we did not have access to the heating system to meter it directly. Yet we would expect that the heat related energy demand of the flats would most likely have dwarfed the IT and appliance use that we could measure in both energy and carbon footprint terms. This limitation is highly relevant if one were using our findings to set policy or to consider the building's carbon footprint holistically.

Similarly, even where we had all 8 study bedrooms in a flat, finely instrumented, as with Bates et al. (2012), we were never able to fully account for the gap between the sum of the fine-grained energy data and the whole flat's energy meter. We knew the magnitude of this gap, but we were unable to be more specific about how it was composed. We named this

gap 'dark energy'. We attributed it to unknown and un-inventoried devices hardwired into the flat circuits (communal lights, alarms, meters, and so on.), and the participants who 'opted out' of the study and thus did not have sensors installed.

It's worth noting also that participants under observation may well adjust what they are doing—for example, avoiding practices deemed too sensitive or embarrassing—or as in one memorable case, providing us with an unexpected message in 'artfully arranged tea-bags'! In our home router study (Widdicks et al. 2019), we made an explicit allowance for this: devices could bypass our research WiFi router to allow for unrecorded Internet activity to offer a degree of privacy. Remembering what we might be missing or are deliberately excluding, and its estimated magnitude, is important for putting our measured findings into the appropriate context. Secondary data can be valuable to validate how observations at a household scale correlates or differs from macro trends (e.g. Sandvine 2019).

There is of course additional work and cost for the research team over traditional interview

methods in establishing new primary data through experimental deployments in this way. There are very real ethical and practical concerns to negotiate; we clearly have a responsibility to be mindful of intrusion into the private lives of participants to get the detailed data needed. Plus, there is always a surprising amount of time associated with installing, maintaining and recovering equipment before, during and after the study (Tenddez, Widdicks, and Hazas 2018). We now try to make use of commercial devices where possible (wildlife camera, per-socket power sensors, temperature data loggers) rather than our own hybrid solutions to increase robustness and reliability. Naturally, all equipment has to be calibrated and tested to ensure robustness and secure data storage capacity to ensure measurements will be reliably gathered for the study duration.

Interpreting rich data can take considerable time before the interviews; particularly when balancing this against the wish to hold the interviews while the experience is still fresh in the minds of our participants. The ‘hobcam’ from our food preparation study (Clear et al. 2013a) is an ideal example of this: a simple-to-deploy technology, but time-consuming to analyse, yielding thousands of images—each to be coded for content, cooking technique and linked to the cooker’s timed energy data. This was a largely manual process. We have usually needed to write software or ‘scripts’ to automate some of this data processing, and have learnt to get this ready before the study commences.

As with any complex composition of hardware and software, we have learnt to expect sensor failures, missing data, or an unexpected unplugging, restarting, powering off or move of devices during a study. To some extent, participant briefings and labelling sensors with ‘please do not unplug’ help, but it’s hard to anticipate what can go wrong: a non-household resident unplugging the system to use a vacuum cleaner every week being a particularly memorable

example from an early study! We heartily recommend a test deployment with research team members to iron out teething problems and uncover any problems with methodology, data or setup. Some ‘settling time’ is recommended at the start of the study to skip novelty related effects before gathering the ‘real data’. We’ve nearly always gathered a greater volume of data than we needed, so our best advice is to think carefully about how to achieve a reliable experimental design with minimum complexity and a sufficiency of data.

Recognising that practices often exhibit particular temporal rhythms, we aim to run the logging period for sufficiently long to intersect with these rhythms. We have learnt to appreciate the need to timestamp the data, crucial for aligning streams so that the timing, repetition, frequency, and relative ordering of energy events and how these might relate to the practices mentioned in the accounts of our participants are more obvious. Care is required to ensure the various clocks and timestamps are sufficiently well aligned from the start, with particular attention to how timezone and daylight savings time adjustments are handled (especially if they could change during the study) to avoid later complications.

To varying degrees, specialist programming and data handling skills are needed to transform data of this kind into something usable and useful. Establishing and maintaining the measurement system during the study and engaging with the households brings with it additional responsibilities and pressures. Again, using commodity data loggers and off-the-shelf devices and toolkits are recommended to make this kind of data gathering less specialized and more reliable.

### **5.3. Being mindful of privacy and ethics**

Deploying technology to record activity in the home naturally raises ethical and privacy

concerns. It exposes participants lives to the researchers, as with ethnographic or video based observation, though often in minute detail. The use of data loggers and environmental sensors such as temperature also surfaces other dynamics of household practices which might be otherwise hidden, for example, details of home life that some in the household are not aware of, or would prefer to keep private.

Clearly, one should not introduce technology into the home without due consideration to these sensitivities. As a general principle, we have avoided the use of high-fidelity recording devices (audio and video), and while we audio-record interviews, all of our studies require participant consent in advance. It's important to think carefully about sensing type used, minimum sufficient area of coverage, location of sensors, and so on. It is also important to consider how often researchers should expect to access the data or loggers to avoid continually interrupting the household (influencing the study and inconveniencing participants), and how to securely access or transport the resulting data to maximize security.

While our study methods are clearly intrusive, we think its useful to note that all of our studies had institutional ethics approval and participant consent. We are in no way advocating the permanent installation of this kind of surveillance technology longer term. However, it is important to add, that the cost of integrating these and even far more intrusive sensing such as cameras, microphones, energy sensors and network loggers, is an everyday reality that is affordably integrated into commercial products. Indeed, many households choose not to just allow, but positively invite and pay for this to be the case (cf. Smart Speakers, voice controlled Smart TVs, and the like). Our approach therefore, can also provide a glimpse into the insights that might be available from the perspective of these now everyday smart home appliances.

## 6. Concluding remarks

The complexity of the home, growing footprint of digital and connected devices, and well known yet hard-to-explain differences in energy demand make domestic environments a challenging but important site for study. We have provided comprehensive treatment of our Resource Trace Interviewing approach which combines the understanding of resource use and practices from sensors deployed in the home, with qualitative accounts (interviews, diaries, home tours) to interpret and develop understandings from these data. This brings forth the routine, mundane and the exceptional by linking domestic practices with connected device and appliance use to energy and other resource and emission impacts.

This approach gathers insights from throughout the study as an extension of visual and trace-driven interview techniques to elicit accounts and make sense of the impacts of domestic practice. But it also allows us to 'datify' and look at the patterns, repetition and magnitude of resources associated with device use in the home. This has allowed us to understand the role of technologies and repeated performance of practices in constituting types of demand. We have unpicked how different digital technologies are carefully assembled to support practices in various levels of fidelity and meaning (Bates et al. 2012). Relatively similar practices are supported, but with markedly different energy footprints, or patterns situated in time. This contributes to our understanding of the drivers in variation of energy demand, and of the diversity in the performance of practices in the home.

Importantly, we do not see quantitative and qualitative methods as being separate, but rather complementary and dialectic. In their combination, contextual factors and measures of activities can shape, sensitize and elicit accounts, amplifying their power to reveal the home in all its ordinariness, richness and variation. We have used, and continue to use and

adapt Resource Trace Interviewing in different studies and study contexts, including: thermal comfort in shared offices; vehicle and worker movements in last mile logistics; fairness and sustainability of gig economy deliveries; and, explaining energy demand in non-domestic settings. Mindfully and carefully applied, we believe our method to be a powerful addition to the arsenal of techniques for studying and interpreting the impact of practices, including but not limited to, energy demand in the home.

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## Notes on contributors

*Adrian Friday* is Professor of Computing and Sustainability at Lancaster University, UK. His work focuses on how ubiquitous systems, data and empirical studies reveal the externality and impacts of everyday life, and offer new and more sustainable ways of doing. He has led a series of collaborative and multi-disciplinary research projects exploring energy use in the home, thermal comfort, sustainable food shopping, and last-mile logistics. His latest work focuses on environmental and social justice for gig economy, and a significant new programme exploring time

series statistics, HCI & human geography and machine learning might provide energy insights toward net zero. He is an advisor to the leading Ubi-comp journal, IMWUT; and a member of the Royal Society ‘‘Digital Technology and the Planet’’ working group responsible for advising on policy for ICT toward sustainable digital society.

*Mike Hazas* is Professor at Department of Information Technology, Division of Visual Information and Interaction, Uppsala, Sweden. His research is concerned with everyday practices and digital technologies, and how they can be related to sustainability (energy demand and carbon emissions). Much of his recent work has focused on the proliferation of online services (streaming, social networking, gaming); and their invisible impacts due to the Internet and data centres. He has also spent significant time researching thermal comfort; and digital automation. He employs both qualitative and quantitative approaches.

*Dr. Oliver Bates* is a Research Fellow at Lancaster University, UK. Motivated by growing environmental impact and social injustice his research focuses on how computing and data science can be utilised to promote environmental sustainability and social justice. His research involves close collaboration with end-users, industry and policy makers, leveraging user research, data science and digital technology. His current work focuses on: collaborative and low-carbon freight deliveries in urban environments; developing digital platforms that promote both social justice and sustainability for gig-economy food and parcel delivery workers; and designing decision support tools that leverage big, heterogeneous data in smart cities and campuses that promote reductions in energy consumption and pollution.

*Janine Morley* is an Early Career Research Fellow at Lancaster University, UK, and holds a PhD in the sociology of energy demand, a field in which she continues to specialise. Her research interests include the role of clothing in the transition to lower carbon heating, the growth of everyday forms of internet connectivity, and the relations between social practices and environmental impacts. Much of her work is interdisciplinary, collaborative and involves combinations of methods which she uses to advance theories of practice and contribute sociological insights to the fields of energy research and human computer interaction.

*Dr. Carolynne Lord* is a Senior Research Associate at Department of Sociology, Lancaster University,

UK. Her work has explored the role of personal digital devices and mobile technologies in the digitally connected home, including digital tablets and their relation to changing social practices and interconnections. Much of her work is interdisciplinary and collaborative, and brings a socio-theoretical perspective to areas where digital technologies are impacting other domains including platform and gig-economic work, and issues of social justice.

**Dr. Kelly Widdicks** is a Lecturer in Computer Science in the School of Computing and Communications at Lancaster University. Her research focuses on the sustainable and responsible innovation of digital technology, and she is experienced in both quantitative and qualitative Human-Computer Interaction methods. Her research on sustainable video streaming and the climate impacts of ICT has gained international and national media attention, including live interviews for BBC Radio 5 Live and BBC Radio Scotland. She is currently a co-investigator of the EPSRC-funded Paris-DE project (EP/V042378/1) which aims to develop a responsible innovation framework for sustainable digital technology.

**Dr. Gormally-Sutton** is a human geographer with a background in energy geographies. She has undertaken research across the energy sphere including recent work on the role of invisible energy policy in Higher Education Institutions (HEI's) and is a part of the Supergen Energy Storage Network + (Ref: EP/SO322622/1). Dr Gormally-Sutton often takes an interdisciplinary approach in her research, working collaboratively with other disciplines. She has worked collaboratively with geoscientists, engineers and computer scientists and has also been involved in research with Energy Lancaster, a cross-faculty research centre that aims to address societal challenges around sustainability and security of energy. Dr Gormally-Sutton now leads Energy Lancaster's theme on 'Energy & Society'. Dr Gormally-Sutton has published in peer-reviewed journals such as Energy Policy, Energy Research and Social Science, and Geoforum.

**Dr. Adrian Clear** is a lecturer in the School of Computer Science at National University of Ireland, Galway. His research in Human-Computer Interaction is concerned with relationships between digital technology and interaction design, data, and sustainability. It investigates what data can reveal about the complexities of everyday life and the impacts of pervasive and ubiquitous computing technologies, including how people make sense of their data in terms of everyday practices. It explores issues of

participation in current trajectories and future visions of smart technologies and cities, and how interactive and information systems can be designed to support participatory negotiations of sustainable futures.

## References

- Bagnoli, A. 2009. "Beyond the Standard Interview: The Use of Graphic Elicitation and Arts-Based Methods." *Qualitative Research* 9 (5): 547–570.
- Bates, O. 2015. "The Impacts of Domestic Media and ICT: A Study of Digital Technology, Energy Consumption, Data Demand and Everyday Practice." PhD Thesis, Lancaster University (United Kingdom).
- Bates, O., A. Clear, A. Friday, M. Hazas, and J. Morley. 2012. "Accounting for Energy-Reliant Services within Everyday Life at Home." In *Pervasive Computing, Proceedings 10th International Conference, Pervasive 2012*, edited by J. Kay, P. Lukowicz, H. Tokuda, P. Olivier, and A. Krüger, 107–124. Newcastle: Springer.
- Bates, O., M. Hazas, A. Friday, J. Morley, and A. K. Clear. 2014. "Towards an Holistic View of the Energy and Environmental Impacts of Domestic Media and IT." In *Proceedings of the Sigchi Conference on Human Factors in Computing Systems*, 1173–1182. New York: ACM.
- Benford, S., D. Rowland, M. Flintham, R. Hull, J. Reid, J. Morrison, K. Facer, and B. Clayton. 2004. "Savannah: Designing a Location-Based Game Simulating Lion Behaviour." In *International Conference on Advances in Computer Entertainment Technology*. Singapore.
- Bittle, R. G., R. Valesano, and G. Thaler. 1979. "The Effects of Daily Cost Feedback on Residential Electricity Consumption." *Journal of Behavior Modification* 3 (2): 187–202.
- Braun, V., and V. Clarke. 2006. "Using Thematic Analysis in Psychology." *Qualitative Research in Psychology* 3 (2): 77–101.
- Brynjarsdóttir, H., M. Håkansson, J. Pierce, E. P. Baumer, C. DiSalvo, and P. Sengers. 2012. "Sustainably Unpersuaded: How Persuasion Narrows Our Vision of Sustainability." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 947–956. New York: ACM.
- Cisco. 2019. "Cisco Visual Networking Index: Forecast and Trends, 2017–2022." Technical Report. Cisco. Accessed September 2019. <https://www.cisco.com>

- com/c/en/us/solutions/collateral/serviceprovider/visualnetworkingindexvni/whitepaper11741490.pdf.
- Clear, A., A. Friday, M. Hazas, and C. Lord. 2014. "Catch My Drift? Achieving Comfort More Sustainably in Conventionally Heated Buildings." In *Proceedings of the 2014 Conference on Designing Interactive Systems*, 1015–1024. New York: ACM.
- Clear, A., M. Hazas, J. Morley, A. Friday, and O. Bates. 2013a. "Domestic Food and Sustainable Design: A Study of University Student Cooking and Its Impacts." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2447–2456. New York: ACM.
- Clear, A. K., J. Morley, M. Hazas, A. Friday, and O. Bates. 2013b. "Understanding Adaptive Thermal Comfort: New Directions for Ubicomp." In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, 113–122. New York: ACM.
- Costanza, E., S. D. Ramchurn, and N. R. Jennings. September, 2012. "Understanding Domestic Energy Consumption Through Interactive Visualisation: A Field Study." In *14th ACM International Conference on Ubiquitous Computing*, 216–225. New York: ACM. <http://eprints.soton.ac.uk/338804/>.
- Crilly, N., A. F. Blackwell, and P. J. Clarkson. 2006. "Graphic Elicitation: Using Research Diagrams As Interview Stimuli." *Qualitative Research* 6 (3): 341–366.
- Cuce, E. 2016. "An Overview of Domestic Energy Consumption in the UK: Past, Present and Future." *International Journal of Ambient Energy* 37 (4): 428–435.
- Dillahunt, T., J. Mankoff, E. Paulos, and S. Fussell. 2009. "It's Not All about 'Green': Energy Use in Low-Income Communities." In *Proceedings of the 11th International Conference on Ubiquitous Computing*, 255–264. New York: ACM.
- DiSalvo, C., P. Sengers, and H. Brynjarsdóttir. 2010. "Mapping the Landscape of Sustainable HCI." In *Proceedings of the 28th International Conference on Human Factors in Computing Systems*, 1975–1984. New York: ACM.
- Dubois, E., and H. Ford. 2015. "Qualitative Political Communication — Trace Interviews: An Actor-Centered Approach — Qualitative Political Communication — Trace Interviews: An Actor-Centered Approach." *International Journal of Communication* 9: 25.
- Durkheim, E., and J. W. Swain. 2008. *The Elementary Forms of The Religious Life*. London: Courier Corporation.
- Eon, C., J. Breadsell, G. Morrison, and J. Byrne. 2019. "Shifting Home Energy Consumption Through A Holistic Understanding of The Home System of Practice." In *Decarbonising the Built Environment*, 431–447. Singapore: Springer.
- Firth, S., K. Lomas, A. Wright, and R. Wall. 2008. "Identifying Trends in the Use of Domestic Appliances from Household Electricity Consumption Measurements." *Energy and Buildings* 40 (5): 926–936.
- Freitag, C., M. Berners-Lee, K. Widdicks, B. Knowles, G. S. Blair, and A. Friday. 2021. "The Real Climate and Transformative Impact of ICT: A Critique of Estimates, Trends, and Regulations." *Patterns* 2 (9): 100340.
- Geiger, R. S., and D. Ribes. 2011. "Trace Ethnography: Following Coordination Through Documentary Practices." In *2011 44th Hawaii International Conference on System Sciences*, 1–10. IEEE.
- Gram-Hanssen, K. 2007. "Teenage Consumption of Cleanliness: How to Make It Sustainable?" *Sustainability: Science, Practice, and Policy* 3 (2): 15–23.
- Gram-Hanssen, K. 2010a. "Residential Heat Comfort Practices: Understanding Users." *Building Research and Information* 38 (2): 175–186.
- Gram-Hanssen, K. 2010b. "Standby Consumption in Households Analyzed With a Practice Theory Approach." *Journal of Industrial Ecology* 14 (1): 150–165.
- Gronow, J., and A. Warde. 2001. *Ordinary Consumption*. New York: Routledge.
- Grunewald, P., and M. Diakonova. 2018. "The Electricity Footprint of Household Activities – Implications for Demand Models." *Energy and Buildings* 174: 635–641.
- Hand, M., E. Shove, and D. Southerton. 2007. "Home Extensions in the United Kingdom: Space, Time, and Practice." *Environment and Planning D: Society and Space* 25 (4): 668–681.
- Hargreaves, T., M. Nye, and J. Burgess. 2010. "Making Energy Visible: A Qualitative Field Study of How Householders Interact with Feedback From Smart Energy Monitors." *Energy Policy* 38 (10): 6111–6119.
- Harper, D. 2002. "Talking About Pictures: A Case for Photo Elicitation." *Visual Studies* 17 (1): 13–26.

- Jupp, V. 2006. *Visual Methods*. 1 vols. London: SAGE Publications.
- Kawsar, F., and A. B. Brush. 2013. "Home Computing Unplugged: Why, Where and When People Use Different Connected Devices at Home." In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, 627–636. New York: ACM.
- Lord, C., M. Hazas, A. K. Clear, O. Bates, R. Whittam, J. Morley, and A. Friday. 2015. "Demand in My Pocket: Mobile Devices and the Data Connectivity Marshalled in Support of Everyday Practice." In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 2729–2738. New York: ACM
- Morley, J. 2014. "Diversity, Dynamics and Domestic Energy Demand: A Study of Variation in Cooking, Comfort and Computing." PhD Thesis, Lancaster University (United Kingdom).
- Morley, J., and M. Hazas. 2011. "The Significance of Difference: Understanding Variation in Household Energy Consumption." In *ECEEE Proceedings 2011 Summer Study*, 2037–2046. ECEEE.
- Morley, J., K. Widdicks, and M. Hazas. 2018. "Digitalisation, Energy and Data Demand: The Impact of Internet Traffic on Overall and Peak Electricity Consumption." *Energy Research & Social Science* 38: 128–137.
- Petersen, J. E., V. Shunturov, K. Janda, G. Platt, and K. Weinberger. 2007. "Dormitory Residents Reduce Electricity Consumption when Exposed to Real-time Visual Feedback and Incentives." *International Journal of Sustainability in Higher Education* 8 (1): 16–33.
- Pierce, J., D. J. Schiano, and E. Paulos. 2010. "Home, Habits, and Energy: Examining Domestic Interactions and Energy Consumption." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1985–1994. New York: ACM
- Pink, S., and K. Leder Mackley. 2013. "Saturated and Situated: Expanding the Meaning of Media in the Routines of Everyday Life." *Media, Culture & Society* 35 (6): 677–691.
- Pink, S., K. L. Mackley, V. Mitchell, M. Hanratty, C. Escobar-Tello, T. Bhamra, and R. Morosanu. September, 2013. "Applying the Lens of Sensory Ethnography to Sustainable HCI." *Transactions on Computer-Human Interaction* 20 (4): 1–18.
- Reckwitz, A. 2002. "Toward a Theory of Social Practices A Development in Culturalist Theorizing." *European Journal of Social Theory* 5 (2): 243–263.
- Rogers, Y., S. Price, G. Fitzpatrick, R. Fleck, E. Harris, H. Smith, C. Randell, et al. 2004. "Ambient Wood: Designing New Forms of Digital Augmentation for Learning Outdoors." In *Proceedings of the 2004 Conference on Interaction Design and Children: Building A Community*, 3–10. New York: ACM
- Røpke, I., and T. H. Christensen. 2012. "Energy Impacts of ICT – Insights from an Everyday Life Perspective." *Telematics and Informatics* 29 (4): 348–361. Green Information Communication Technology.
- Sandvine. 2019. "Global Internet Phenomena Report." Technical Report. Sandvine Incorporated ULC.
- Shove, E. 2003. *Comfort, Cleanliness and Convenience: The Social Organization of Normality*. Oxford: Berg.
- Shove, E., and H. Chappells. 2013. "Ordinary Consumption and Extraordinary Relationships: Utilities and Their Users. In *Ordinary Consumption*, 53–66. New York: Routledge.
- Shove, E., and G. Walker. 2014. "What is Energy for? Social Practice and Energy Demand." *Theory, Culture & Society* 31 (5): 41–58.
- Southerton, D. 2006. "Analysing the Temporal Organization of Daily Life: Social Constraints, Practices and Their Allocation." *Sociology* 40 (3): 435–454.
- Southerton, D. 2013. "Habits, Routines and Temporalities of Consumption: From Individual Behaviours to the Reproduction of Everyday Practices." *Time & Society* 22 (3): 335–355.
- Strengers, Y. 2014. "Smart Energy in Everyday Life: Are You Designing for Resource Man?" *Interactions* 21 (4): 24–31.
- Tendedez, H., K. Widdicks, and M. Hazas. December, 2018. "Planning for the Things You Can't Plan for: Lessons Learned From Deployments in the Home." *Interactions* 26 (1): 52–57.
- Walker, G. 2014. "The Dynamics of Energy Demand: Change, Rhythm and Synchronicity." *Energy Research & Social Science* 1: 49–55.
- Wall, R., and T. Crosbie. 2009. "Potential for Reducing Electricity Demand for Lighting in Households: An Exploratory Socio-Technical Study." *Energy Policy* 37 (3): 1021–1031.
- Warde, A., S. L. Cheng, W. Olsen, and D. Southerton. 2007. "Changes in the Practice of Eating: A Comparative Analysis of Time-Use." *Acta Sociologica* 50 (4): 363–385.

- Widdicks, K., O. Bates, M. Hazas, A. Friday, and A. R. Beresford. 2017. "Demand Around the Clock: Time Use and Data Demand of Mobile Devices in Everyday Life." In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, edited by Gloria Mark, Susan R. Fussell, Cliff Lampe, m. c. schraefel, Juan Pablo Hourcade, Caroline Appert, and Daniel Wigdor, 5361–5372. New York: ACM.
- Widdicks, K., M. Hazas, O. Bates, and A. Friday. 2019. "Streaming, Multi-Screens and YouTube: The New (Unsustainable) Ways of Watching in the Home." In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, edited by Regan L. Mandryk, Stephen A. Brewster, Mark Hancock, Geraldine Fitzpatrick, Anna L. Cox, Vassilis Kostakos, and Mark Perry, 1–13. New York: ACM.
- Wilhite, H., and R. Ling. 1995. "Measured Energy Savings from a More Informative Energy Bill." *Energy and Buildings* 22 (2): 145–155.
- Zerubavel, E. 1979. *Patterns of Time in Hospital Life*. Chicago: University of Chicago Press.