Towards an Holistic View of the Energy and Environmental Impacts of Domestic Media and IT

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ABSTRACT
To date, research in sustainable HCI has dealt with eco-feedback, usage and recycling of appliances within the home, and longevity of portable electronics such as mobile phones. However, there seems to be less awareness of the energy and greenhouse emissions impacts of domestic consumer electronics and information technology. Such awareness is needed to inform HCI sustainability researchers on how best to prioritise efforts around digital media and IT. Grounded in inventories, interview and plug energy data from 33 undergraduate student participants, our findings provide the context for assessing approaches to reducing the energy and carbon emissions of media and IT in the home. In the paper, we use the findings to discuss and inform more fruitful directions that sustainable HCI research might take, and we quantify how various strategies might have modified the energy and emissions impacts for our participants.

Author Keywords
Home energy; sustainability; embodied emissions; life cycle assessment.

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

INTRODUCTION
The domestic energy demand of consumer electronics, digital home entertainment and computing devices (which we will call *media and IT* in this paper) is on the rise worldwide [5]. Between 2000 and 2009 IT consumption in the UK more than doubled [16]. These devices comprise about 25% of the total domestic electricity demand [17]. Despite the fact that these devices are individually becoming more efficient, the total energy use of these devices continues to rise [16]. While the HCI and ubicomp communities have considered ways to reduce media and IT's environmental and energy impacts, these have tended to focus on issues such as improved computer power management [4], understanding device attachment [15], or eco-feedback [7]—what is lacking is a broader view of the impacts of media and IT at home, and how these relate to everyday practice.

With the growing ownership of media and IT devices, we attempt to answer several more contextual questions, such as: how are all these devices used in everyday life? What are the resource and environmental impacts of these configurations, and how is this related to their implication in practice? What are the links between variation in similar practices, and variation in impacts? With answers to these questions, sustainable HCI might be better equipped to identify and pursue new avenues of research and design.

Based on in-depth studies involving 33 students living in on-campus university accommodation, we explore the media and IT device inventories, the day-to-day practices that they support, their measured direct energy demand, and their approximate embodied greenhouse gas emissions. We put forth three contributions. (1) We quantify the embodied carbon and direct energy of domestic media and IT using participant inventories and energy-use data. To date, studies of domestic technology in sustainable HCI haven't included embodied emissions; we believe the inclusion of these impacts, alongside direct energy, is crucial to better understanding the wider 'sustainability picture'. (2) We link the variation in these impacts to the role that these technology configurations play in supporting our participants' everyday practices. In so doing, we develop and explore the prominence of *constellations* and *connoisseurs*, two concepts which we briefly introduced [2, p. 15–16] in our discussion of domestic energy use. (3) Based on our findings, we discuss the potential impact reductions of specific solutions previously proposed in the HCI literature, and go on to highlight some new implications for design.

RELATED WORK AND MOTIVATION
The concern with direct and indirect impacts of appliances and devices has been a consideration for some years in HCI. Direct energy impact is a particular sensitivity for those involved in so called 'eco-feedback' technologies, as surveyed by Froehlich et al. [9] and exemplified in recent domestic eco-feedback interventions [8]. While eco-feedback aims to promote understanding and awareness of how energy is spent [7] and encourage energy saving behaviours [8], such technologies have not been found to be particularly effective. Moreover, eco-feedback has been critiqued for casting individuals as 'rational actors', and failing to recognise that energy use is intertwined with everyday practices [22]. In our paper, we concern ourselves with understanding the impacts, and con-

CHI 2014, April 26–May 1, 2014, Toronto, Ontario, Canada.

http://dx.doi.org/10.1145/2556288.2556968

nection between media and IT and everyday practices, in the home.

Energy use related to IT in the home has been studied previously. Chetty et al. found power management strategies on home computers were often underused [4]. Pierce et al. similarly found an unwillingness to power down or 'micro-manage' IT devices [19]. Reinforcing Strengers [22], Pierce observes how our everyday interactions with home appliances more broadly, are unconscious or habitual rather than the result of rational decision-making, and proposes a design vocabulary of energy saving behaviours. We consider largely personal media and IT appliances, and while time of use is sometimes a factor in our study, we do not concern ourselves directly with the practices surrounding power management.

Of course, the direct energy demand of media and IT hardware, its peripherals, and supporting infrastructure within the home are only a part of the story. A more complete view of media and IT's impacts should include: the *embodied* greenhouse gas emissions arising from manufacturing and transport of hardware (hereafter *embodied emissions*); the *direct* energy impacts of the devices themselves; and the *indirect* impacts (embodied emissions and direct energy) of the network infrastructure, computation and data storage relied upon, far outside the home.

While there appears to be little quantification of these embodied and indirect impacts in the HCI literature, it is true to say that reducing these impacts have been widely acknowledged: in Blevis's influential paper [3], several Sustainable Interaction Design principles are elucidated, challenging designers to consider the disposal of old technology in the invention of new ones, and exhorting the incorporation of renewal and reuse in design. Wakkary and Tanenbaum build on these principles to show how families appropriate and extend everyday technologies for continued use [24].

The longevity of device use (over which embodied impact is defused) is considered with respect to mobile phones by Huang and Truong [12] in 2007. The style and features of a phone do not spur phone upgrades, so much as end-of-contract and special offers from mobile phone carriers. Hanks et al. covered university students' attitudes toward environmental issues, and their purchasing of mobile phones and computers [11]: respondents showed an openness to refurbishment and contributing to responsible disposal, yet there was a high rate of device replacement across relatively short time periods (especially for phones), a reticence to buy used and refurbished phones and laptops, and an unwillingness to share these devices.

Odom et al. looked more broadly at the reasons people feel attachment to certain possessions, and make efforts to preserve them [15]. He noted relatively little attachment to digital artefacts, and discussing the design of more enduring objects. More recently, Gegenbauer and Huang considered how attachment is a critical factor for influencing the longevity of device ownership, and how appliances that have fallen out of use are far more likely to be kept 'just in case' than disposed of [**?**]. Kim and Paulos develop a framework for the creative reuse of e-waste based on surveys of personal stockpiling behaviours [13].

In our work we focus on offering a holistic view of the impacts of media and IT appliances for a university student population. We quantify both the direct energy and embodied impacts of these appliances and link these to the everyday practices they support.[1] Our goal is to help sustainability researchers decide where best to apply their efforts by highlighting the stark variations in impact, and relating these to specific configurations of everyday practice and technology.

METHODS AND DATA GATHERED

In this paper we are focusing on three areas of impact: embodied emissions, direct energy, and indirect impacts. We provide quantitative measures of embodied emissions (in the form of kilograms of carbon dioxide equivalent, abbreviated kg CO_2e), and of direct energy (in kilowatt-hours). Despite our detailed study methods, the indirect impacts (e.g. those arising from Internet service, mobile cellular data, and data centres) were not quantifiable. However, we use interview data to qualitatively comment on the frequency and role of these services in our participants' lives, and we make specific suggestions for how indirect impacts might be accounted for in future enquiry.

A mixed-methods approach was used to study media and IT in the homes of student participants living on campus at university. The findings in this paper are based on data collected across three different studies (Table 1). One study was undertaken in March 2011 by Bates et al. [2], and we are utilising the data from twenty-one of their participants.[2] The second study was conducted by Clear et al., and involved four participants during March–April 2012 [6].[3] The third study involved eight participants in November 2012.

The students had private study-bedrooms arranged around a central corridor with shared kitchen. Their devices (Table 2) occasionally were shared, however these weren't communal or "common-use" devices.

For the participants across all three studies, device and appliance inventories were taken on an initial visit to their room. Plugwise socket-monitors were used to capture the fine-grain energy consumption data for a total of 191 devices over several weeks from each study. Semi-structured interviews were

[1]While we acknowledge disposal or recycling of a product is an important component in its overall footprint, we neglect it for the purposes of this paper. Recycling and disposal methods are highly dependent on locality, and for IT, the greenhouse emissions impacts are relatively low compared to manufacturing, transportation, and usage (typically less than 5%).

[2]Bates et al. report on 'entertainment and IT' using a subset of the data [2, pp. 112-5]. It is important to note that their characterisation was relatively brief and primarily qualitative; they only quantified the direct laptop/desktop energy for nine of their participants. By contrast, this paper leverages the per-socket sensor data for twenty-one participants from that study, and twelve more from later studies, to bring out new, insightful details of both direct energy variation, and embodied emissions.

[3]Clear et al. wrote about thermal comfort in the lives of the participants; the per-socket energy data and the interviews on media and IT have not been previously reported.

Study	Study Period	Participants	Interviewed Participants	Total Devices
1	March 2011 - April 2011	21	11	127
2	March 2012 - April 2012	4	4	21
3	November 2012	8	8	43
Total	-	33	23	191

Table 1. Summary of the media and IT studies

used to help understand the role of media and IT devices in the day-to-day lives of our participants. The interviews were fully transcribed and coded. In our discussion below, we refer to each of the 33 participants using pseudonyms. Per-socket energy consumption data in the latter two studies has been limited to a representative 20-day window during term time, to be comparable with the first study.

Limitations and assumptions

We acknowledge that students' media and IT practices are not necessarily generalisable (e.g. accessing a VLE). However, students are a specific and sizeable demographic: 7% of the UK population, and 15% of the US. Similar IT related practices are described in 14 Danish homes by Røpke et al. [20]. Compared to other areas of practice (e.g. laundry, home heating, cooking), there may be more parallels between the IT of students, and other parts of the population. Regardless, we should stress that our goal is not generalisability *per se*, but rather to richly characterise *variations* in practice, technology and impact.

Since the lifetimes of our participants' devices were not known (the devices all remained in use during the study), we show the approximate embodied carbon (e.g. Figures 1 or 2) that would have arisen from the manufacture and transportation of a single device of that type. And while as a long term goal we aim to include cloud and content distribution networks (CDNs) in our impact analysis, we are unable to cover this in detail in this paper. Indirect (cloud and CDN) impacts are problematic to measure, as they depend on traffic, network path, data centre location and power source. However, to give a feel for how these contribute, we do give examples of what some of the relative impacts might be, based on our qualitative data.

INVENTORIES

Across all 33 participant rooms, there were a total of 191 devices and appliances (Table 2). There were 50 appliances that did not explicitly support media and IT related services (e.g. hair dryers, hair straighteners, coffee machines, kettles, alarm clocks, fans, and a toothbrush charger). While we list these in the table for completeness, we focus our analysis on the remaining 138 media and IT devices.

All 33 participants had computers: 29 had just a laptop; 1 had just a desktop; and 3 had both. 16 of the participants had one or more computer monitors or peripherals (e.g. powered speakers, external hard disk drives (HDDs), and printers). 8 participants had TVs, all of which were connected to at least one other device (e.g. DVD player, video game console). The number of media and IT devices and appliances in each room

Participant	Constellations	Non constellation media and IT devices	Other Devices	No. Devices	Total Constellations
Zoe	-	Laptop	-	2	-
Ellie	-	Laptop	Kettle	3	-
Thomas	-	Laptop	Alarm Clock	3	-
Aaron	-	Laptop	Alarm Clock	3	-
Wendy	-	Laptop	Hair Dryer	3	-
Jess	-	Laptop	Hair Straighteners	3	-
James	-	Laptop	Lamp	3	-
Jill	-	Notebook -> Laptop	Lamp	4	-
Donna	-	Laptop	Hair Straighteners, Lamp	4	-
Luke	-	Laptop	Lamp, Guitar Amp	4	-
Leah	{TV, Nintendo Wii}	Laptop	-	4	1
Miranda	-	Laptop	Hair Dryer, Hair Straighteners	4	-
Vincent	{Laptop, Laptop Fan}	Camera	-	4	1
Nathan	{Laptop,Speakers,Printer}	-	Toothbrush	5	1
Kevin	{TV, Xbox 360}	Laptop	Alarm Clock	5	1
Polly	-	Laptop	Lamp, Iron, Hair Dryer	5	-
Omar	{TV, Xbox 360}, {Laptop,Speakers}	-	-	5	2
Stan	{Desktop, Monitor}	TV	Hair Dryer	5	1
Darren	{Laptop,Speakers}	Camera	Lamp	5	1
Callum	{Laptop, Monitor, Tube Amp}	-	Coffee Machine, Hair Dryer	6	1
Emily	{Laptop, Printer}	-	Lamp, Kettle, Iron	6	1
Jack	{Laptop, Speakers}	-	Guitar Amp, Lamp, Fan	6	1
Natasha	-	Laptop, Record Player, Camera	Hair Dryer, Hair Straighteners	6	-
Rachel	{Laptop, Printer}	iPod Dock	Hair Dryer, Hair Straighteners, Lamp	7	2
Nadia	{Laptop, Printer}	iPod Dock	Hair Dryer, Alarm Clock, Hair Straighteners	7	1
Chloe	{TV, DVD Player}, {Laptop, Printer}	-	Fan, Alarm Clock	7	2
Kate	{TV, Xbox 360}, {Laptop, Printer}	Stereo, MP3 Player	-	7	2
Stephanie	{TV, Portable HDD}	Laptop	Lamp, Hair Dryer, Hair Straighteners, Toothbrush	8	1
Feng	{TV, Playstation 3}, {Laptop, Speakers}	iPod	Hair Straighteners, Lamp	8	2
Ian	{Laptop, Speakers}, {Laptop, Screen, Speakers}, {Xbox 360, Screen, Speakers}	iPod	Hair Straighteners, Alarm Clock	8	3
Henry	{Desktop, Monitor (2), Router, External HDD (2), Audio Receiver}, {Xbox, Monitor, Audio Receiver}	Laptop	-	10	2
Gary	{Audio Receiver, EQ, CD Player}, {Desktop, Monitor (2), Audio Receiver, Router, NAS}, {Xbox, Monitor, Audio Receiver}	Laptop	Guitar Amp (2)	13	3
Matt	{Laptop, Monitor, Stereo (2), Router, Airport Express}, {TV, IPTV, Stereo (2), Xbox 360, Mac Mini Server, Bluray player}, {Mac Mini Server, USB hub, HDD (2), Router, Airport Express}	-	Coffee Machine, Guitar Amp	18	3

Table 2. Overview of the inventories and constellations for the 33 participants, sorted by increasing number of devices. Mobile and smart phones have been left out as all users owned one, except Gary who owned 2.

ranged from just a few (e.g. Zoe, Ellie and Thomas) to 18 (Matt). Where applicable, brackets in Table 2 shows how the devices were connected as groupings, or what we call *constellations*.

Constellations

We observed people using multiple interrelated devices to perform a task, requiring them to be left on so that a task can be performed without interruption. This is nicely exemplified by Henry, who told us "*I suppose it's not really my computer I use as much but my stereo. I use that a lot, which is connected to my computer*". We consider a constellation to be active when two or more connected or associated devices are consuming electricity at the same time, often working in concert to support the same practice. Constellations are potentially complex, since media and IT devices have a variety of different ways of being connected, both physically or over a wireless network.

From the data collected and analysed we have found that constellations are a crucial entity in understanding media and IT impacts, for three reasons: (1) they are commonplace (there are 30 constellations owned by 20 participants); (2) they are involved in supporting many areas of media and IT practice; and (3) their composition is strongly linked to their embodied emissions and patterns of direct energy consumption.

Embodied Emissions

The field of life cycle analysis (LCA) deals with estimating the embodied emissions that arise from the production and delivery of a certain product or service. Because of the complex and layered nature of materials extraction, processing, manufacturing and transport, it is widely acknowledged that there will be inaccuracies in the overall emissions estimates, particularly for sophisticated products such as media and IT devices. Malmodin et al. [14] surveys previous studies on IT carbon estimations and highlights how a lack of transparency in the surrounding processes of raw-material extraction and manufacturing in LCA leaves a lot of room for error. An in-depth survey of carbon accounting for media and IT devices by Anders et al. shows that typical errors in LCA literature are on the order of about 50%, even for similar products [1].

Despite the relative levels of inaccuracy, it can be informative to (1) compare the embodied emissions of different types of media and IT device, particularly where those devices can be used to deliver similar services; and (2) compare a particular device's embodied emissions, to the carbon that arises due to that device's direct electricity consumption.

Teehan and Kandlikar [23] highlight a lack of LCA performed on newer IT devices. Their results show that there has been a 50–60% decrease in carbon equivalent produced between pre-2004 products and post-2009 products, and that this is due to use of fewer materials. By combining their own mass data and using the 'ecoinvent' database, Teehan et al. show that there is a linear relationship between mass and embodied emissions created in the manufacturing phases of three pre-2004 and eleven post-2009 manufactured devices.

Our embodied emissions figures (see Table 3) use the coefficient reported by Teehan et al. of 27 kg CO_2e per kg of product [23, p. 4002], supplemented by data from Apple whitepapers[4]. Due to their use of ecoinvent, Teehan et al.'s impact coefficients are lower than those of Apple and those reported in the survey by Anders et al. [1]—our embodied impact estimates thus represent *a lower bound* on these impacts, and the actual impacts could be higher.

Figure 1 shows how the estimated embodied emissions are distributed across the inventories of our participants, grouped by device type. All but one participant had a laptop, and these account for about 40% of the total embodied emissions. Displays (monitors and TVs) are the next largest, accounting for 32% of the total embodied emissions.

Before we go on to discuss the impacts, we will give a brief snapshot of media and IT with these participants.

[4]**`http://www.apple.com/uk/environment/reports/`**, accessed September 30, 2014.

	Embodied emissions (kg CO2e)	Mass (kg)	Source
Smart Phone	8	-	Teehan et al.
Desktop	180	-	
Laptop	200	-	
Monitor	190	-	
Mac Mini Server	180	-	Apple Tech Report
TV	405	15	Calculated using 27 kg CO2e per kg of mass. (Teehan et al.)
Computer Peripheral	8.1	0.3	
Games Console	94.5	3.5	
Router/Switch	6.75	0.25	
DVD/Blu-ray Player	67.5	2.5	
CD/Record Player Separate	135	5	
Audio Receiver (Inc. Speakers)	405	15	
Computer Speakers/Dock	62.1	2.3	
Printer	81	3	
Camera	8.1	0.3	
MP3 Player	5.4	0.2	

Table 3. Embodied emissions for media and IT devices that were included in our participants' inventories.

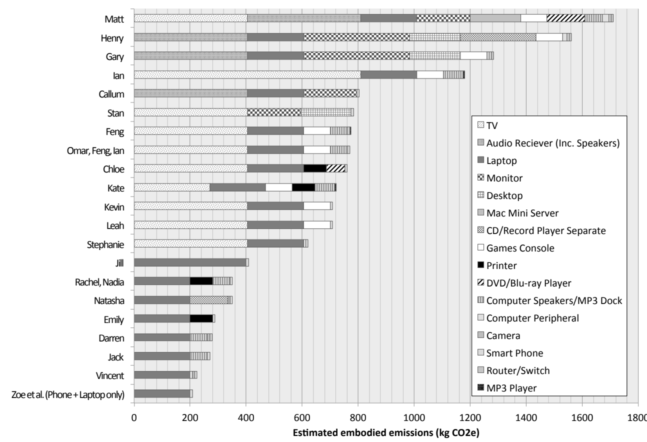

Figure 1. The breakdown of embodied emissions across the 33 inventories.

MEDIA AND IT PRACTICES

Unsurprisingly, we see that media and IT devices feature heavily in the day-to-day activities of our participants. These devices were used for a wide variety of tasks which can broadly be categorised as work, education, entertainment and communication. In this section, we describe some of the more prominent activities in detail. The term 'practice' in this paper is used to describe an activity, or set of actions carried out by our participants.

IT devices

The principal IT devices that we saw were smart phones, and computers, each supporting a variety of practices. In general, we found that desktop and laptop computers were used for similar tasks, and that these tasks were multiple and simultaneous, often related to different practices. For example, instant messaging and email are used to support communication, both personal and work-related, which is often intertwined with work-related tasks such as reading documents for coursework, and essay writing. According to our participants, applications switch in and out of participants' focus as different practices come into play, and interrupt one another. The portability that is characteristic to laptop computers leads to a further blurring of the lines between practices [20].

In general, we found acute awareness of the extent of laptop use. All participants noted using their laptops almost every day, and many participants reported having them on most of the time whilst awake. Our participants used IT for many of the things one might expect: reading blogs or news, browsing, and online shopping. Below, we provide a brief summary of the IT and media practices that featured in the interviews as particularly meaningful to our participants, or were manifest by their specific ways of playing and working.

IT Practices

Social networking and communication practices become difficult to separate from other activities when carried out on IT devices, largely because they are achieved through social media tools like Facebook and Twitter, and instant messengers that support asynchronous communications. In these cases, parties may respond in-between other tasks or even when they are next online. Communication can take place synchronously if all parties are focused on the task, as is generally the case with voice or video chat. For example, Ellie describes her chatting: "*I like Skype my family on the weekends and I Skype my boyfriend, at night usually*". Our participants reported regularly intertwining social networking with work, often as a means of procrastination.

Our participants regularly used their computers for studying and other university work. This usually consisted of using word processors, course-specific software, and the virtual learning environment (VLE) for access to course materials. Some participants stored the documents on their laptops in categorised folders, filling in notes on them during lectures; others kept the VLE open on their laptops for easy access to course content; and some of our participants printed them for revision and use in lectures. Henry used his desktop computer for running and monitoring a test-bed for an outside professional project he was working on.

Media Practices

We found variation in the ways that our participants consumed digital media (e.g. listening to music, watching TV). Quite often, participants reported watching movies and TV on their laptops, using video-on-demand services; from DVD; or downloaded from the Internet. However, three participants mostly watched movies and TV on televisions. Chloe did this using a DVD player, Kate through her Xbox 360, whereas Stephanie would download content to a USB hard drive and watch it on her TV because it had a bigger screen than her laptop. Ian, Donna and Henry mentioned that group film and TV nights would happen occasionally. The hosts of "film nights" tended to be the participants with larger displays or TVs.

Almost all participants reported listening to music. Some had dedicated MP3 players for this. Others used their laptops or mobile phones. In some instances, participants listened to music with multiple devices, using external powered speakers in their rooms into which they could plug their laptops or MP3 players. Darren would bring his laptop and speakers to the kitchen so that his friends could take turns playing songs that they liked. Gary and Natasha had specific media devices for audio playback (CD Player, and record player respectively). Gary and Natasha, reported that audio was often listened to in the background, for instance, whilst studying or getting ready to go about their day.

Nine of our participants owned games consoles. These were either connected to televisions or computer monitors. Henry and Jill did not own consoles, but gamed on their laptops. We saw variation in the extent of use across participants (between 0 and 5 hours per day), and University schedules also affected this. Jill notes how "*Usually in the evening I game before I go to bed,*" whereas Henry recalled how his gaming habits had changed as he became busier with coursework. As Jill notes, gaming is an activity that is often not overlapped with other tasks: *"While I'm gaming I can't do anything else . . . because it takes up the screen."* Group game nights—in a similar vein to group film nights—happened, although less often.

CONFIGURATIONS AND IMPACTS

To give a broader view of impacts of media and IT we discuss the embodied emission impacts of our participants' devices, and then characterise the relationship between the embodied emissions and direct energy consumption. From here, we move onto constellations, focusing on how hub devices are relied upon, and what this means for the direct impact of a constellation. Following this, we examine how connoisseurs of media and IT configure their constellations, along with how this increases direct energy impacts. We conclude with a discussion of the kinds of practices that our participants took part in that lead to indirect impacts, and how Internet-connectedness affects both direct and indirect impacts.

Large embodied emissions, even larger direct energy

In Figure 2 we can see a comparison of estimated embodied emissions footprint alongside the estimated direct carbon emissions over the course of a year. This figure illustrates two things; 1) devices and constellations with larger embodied emissions tend to have greater direct emissions, and 2) the largest quantities of direct emissions are due to large constellations.

For small mobile devices (such as smartphones and tablets), **the direct emissions is vanishingly small compared to the embodied emissions.** Laptops, assuming they have a lifetime of several years, can have comparable direct and embodied emissions, depending on the laptop's daily durations-of-use. But it is important to note that even for the largest, power-hungry constellations on for the majority of the day (as was the case with Henry), the yearly direct emissions still only reached half of the embodied emissions. Thus, while direct energy can be justifiable as a target for reduction through methods such as eco-feedback [22], the embodied emissions should never be underestimated.

Similar practices, different impacts

A constellation becomes subsumed into more practices with the connection of additional IT devices, increasing the impact of a given practice. For example, connection of a laptop to a

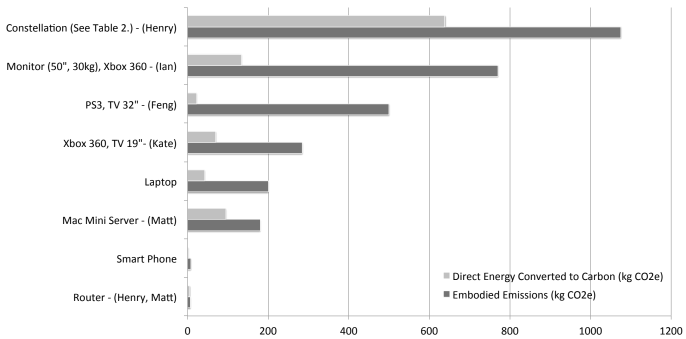

Figure 2. Seven examples of the embodied emissions alongside direct emissions. Embodied emissions values are estimated using the values in Table 3. We based our yearly direct emissions estimate on the 20-day energy we observed in the study, and are calculated using the DEFRA 2010 conversion factor, adjusted to include Scope 3 emissions: 0.60 kg CO_2e/kWh.

display, now enables the use of the display to support practices that would have previously been conducted just using the laptop. Eighteen of our participants had peripherals (e.g. displays, speakers, printers, seen in table 2) for use with their computers. We found that connected devices roughly mimic the time-use patterns of the hub device they are connected to. Small, basic constellations were the lowest contributors (Jack, Ellie, Rachel), for example: a laptop and a couple of peripherals (e.g. printer, speakers). Inventories containing a larger number of media and IT devices (Matt, Henry) contributed between 3.8 and 41.1 times the amount of daily energy when compared to the small constellations (figure 3). If our participants changed their media and IT practices and only used laptops, the total embodied emissions would have been reduced by roughly 55%.

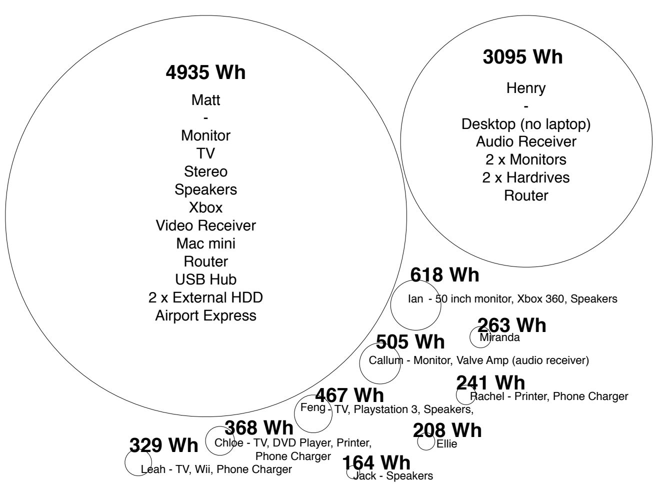

Figure 3. The average daily consumption of 11 participants' devices, demonstrating the variation in inventory and direct energy consumption. Laptops and mobile phones are not listed, as all participants had one of each.

Constellations are interesting in that they are often comprised of a number of not particularly energy intensive devices, yet acting in concert they together consume a significant amount simultaneously (e.g. Nathan's laptop, speakers and printer, or Callum's laptop, monitor and valve amp). A participant might put one device in a constellation to sleep (the laptop), but others (valve amp) might well carry on consuming energy.

Hub devices

Constellations are often configured or set up around a central, hub or basis device, e.g. peripherals connected to a laptop, games console connected to a TV. Among the 31 constellations, we found that laptops were the hub device in 14 of the constellations, desktops in 3 and TVs as the hub in 9 instances. There are 3 occasions where monitors are used instead of TVs; this requires yet another device in the media constellation (e.g. amplifier or powered speakers) so that audio can be provided. It is hard to know when a well-peripheralised hub device is going to be called upon, making low power modes particularly difficult to automate (e.g. knowing when Henry's external HDDs, or Matt's server is needed, figure 4). As a result, we observed hub devices in large constellations powered for all or most of the day (16 – 24 h.).

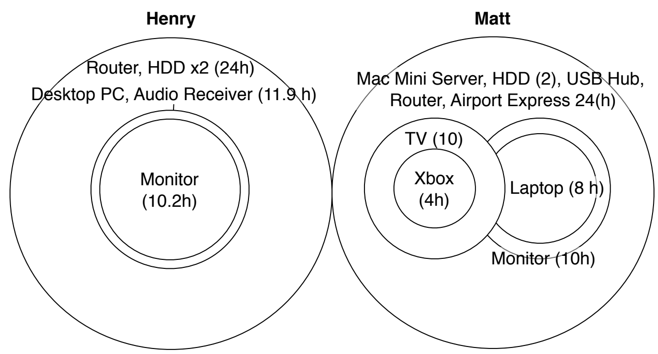

Figure 4. The median daily use-time of Henry's and Matt's constellations. Henry's constellation had a router and 2 external HDDs as always-on, the monitor on average was in sleep (or off) for 2 hours of the desktop's consumption. Matt's always-on infrastructure included a router, Airport Express, Mac Mini Server, 2 external HDDs and a USB hub. There was cross-over of the laptop, and TV constellations, but the laptop and Xbox both relied upon access to the server..

Connoisseurs

The most complex constellations were observed to be owned *by connoisseurs*. We have previously defined media and IT connoisseurs as individuals who "spend more time gaming, working with IT, and watching TV and movies typically with linked complexes of specialised devices" [2]. We elaborate futher on the concept here, and relate it to variations in impacts. Whereas constellations are sometimes configured to support additional practices of the individual, connoisseurs promote meaningful experiences in practice, by for example, adding speakers to a laptop so that the perceived quality of audio is higher.

Evidence of media and IT connoisseurship was observed across 8 of our participants. Four participants (Matt, Callum, Gary, Henry) all had specialised devices for audio playback. Matt used a HI-FI plugged into additional powered speakers for audio. Callum had a tube amp for better appreciation of music and Gary had stereo separates including an amplifier, equaliser, and CD player. Henry also had an amplifier and stereo speakers that were connected to his PC and Xbox. Four other participants had constellations with large TVs specifically for a better visual experience when playing video games (Ian, Feng, Omar, and Kate). Ian had a 50" screen for playing video games with his Xbox, and watching movies.

Among our participants there were two (Henry and Matt) who have constellations that contribute about 42% of the overall media and IT direct energy across all participants. As well as this high direct energy impact their constellations contribute 16.5% of the total embodied emissions. Their constellations contain always-on infrastructure, with one or two constellations layered on top of one another (Figure 4). These connoisseurs have always-on requirements as well as a more customised selection of media and IT devices (e.g. custom desktop computer, dual monitors, IPTV receiver, wireless router, and dedicated audio set ups). This shows that connoisseurship in one area of practice may inadvertently affect impacts of other practices (i.e. the attitude that Henry and Matt have towards quality of experience leads them to own specific devices, and therefore perform similar practices in more energy intensive ways). The connoisseurs not only own constellations (complexes) of devices, they in fact own more constellations, and more specialised devices within those constellations.

Moreover, **media and IT connoisseurs strive for a high quality of service or experience**, choosing to change or upgrade their constellations when circumstance and enthusiasm allow. Henry gives us an account of the upgrades that he performed on his constellation:

> "*Yeah, a lot. A lot different things. In my first year I had er (.) erm I bought my computer, a desktop computer and a single monitor and some cheap speakers, 15–20 quid speakers. And then, and then in my first year I bought a second monitor and some slightly better speakers and I upgraded some of my computer. Er then I bought an external hard drive. Then I my second year I bought a network switch, then some slightly better speakers, I've upgraded the speakers as I've gone, erm, and a better second monitor. ... Then I my third year I brought back even better speakers [laughs]*".

Indirect Impacts

Through analysis of interview data we are able to make observations concerning the practices that contribute to impacts outside of the home (e.g. reliance on Internet based video streaming services, accessing lecture notes through VLE, audible notifications on mobile devices that occurred during interviews).

Frequency of access and total data amount

Internet connectedness is a salient attribute of a majority of practices supported by media and IT devices. The streaming of media, social networking, mobile and laptop notifications, video gaming and education (VLE usage) illustrates that our participants relied heavily on the connectedness of their devices, even without explicitly mentioning being 'connected'.

All 23 interviewed participants used the Internet to access course materials (e.g. assignments, lecture slides) for studying. 22 relied on streaming websites or other Internet-based services for TV watching. Callum "*downloaded off the Internet rather than live TV*", whilst Ellie mentioned a shared access (with another participant) to a service that allowed her to download TV shows that she watched regularly. Aaron used the Internet to "research" new music, and to download music to fill his iPod.

It is possible to roughly estimate the indirect energy impacts of practices involving Internet-based services by drawing on impact estimates from current scholarly articles, such as those derived by Schien et al. [21]. For example, Ellie's streaming of two hours of TV per day might have added 50% to her typical daily direct energy impact; while Darren's frequent social networking might have incurred an additional 10% to his direct energy impact.

Still, there are some practices that don't require network access. Chloe for example exclusively relied on her TV and DVD player for media content. Other 'un-networked practices' include single player video games (purchased on optical storage), and word processing for an assignment.

Connectedness and the opportunities that 'being connected' provides, seems to **increase direct energy consumption**, because connectedness leads to more frequent, and longer durations of use of media and IT devices. For example, Miranda's laptop provided her with the opportunity to stream video-on-demand content whilst getting ready for a night out. Chloe likes to have her laptop running whilst watching video on her TV so she can see any new messages on Facebook. Jill likes to watch TV on her laptop whilst waking up and eating breakfast, and then has Facebook in the background while she works. These examples of opportunistic connections (video-on-demand whilst getting ready) and maintaining connection (Facebook chat in the background) show us that having a connection allows Internet enabled media and IT activities to become part of practices not strictly reliant on media and IT (e.g. getting ready to go out, eating breakfast).

IMPLICATIONS FOR DESIGN

In this section, we start by discussing how previous HCI sustainability research might have shifted our participants' media and IT impacts. We then outline additional areas for consideration and suggest how new strategies might decrease the impact of media and IT. Our impact analysis of previous work are summarised Table 4.

Power management

As Chetty et al. suggested, laptop and desktop power management software should be modified to support easy configuration and short, reliable computer wake-up [4]; and also that this should be easy to accomplish across wired and wireless networks particularly for media and file servers where instant access has come to be expected (Matt). Based on our observations on durations of daily active use, versus when computers were idling, this could lead to a direct energy reduction of up to 2.5%, where the vast majority of these savings is made with Matt's always-on server.

Device constellations present particular challenges for power management. Direct energy impacts of constellations can

Strategy for change	Scope of effect indicated by our study		
	No. Participants	Direct energy	Embodied carbon
Longer use and more re-use of mobile phones and small portables [Hanks et al. 2008, Huang et al. 2008]	33		2%
Software/hardware designs to double expected IT lifetimes [Odom et al. 2009, Pierce and Paulos 2011]	33		18%
Improve power management interfaces/response times [Chetty et al 2009]	1	2.5%	
Replace desktops with laptops or low-energy servers	3	9.3%	16%
Replace large constellations with laptops	2	40%	
Feedback for engaged connoisseurs [Costanza et al. 2012]	2	7%	

Table 4. The scope of effect when modifying home media and IT's impact. This table shows the possible reduction in impacts as suggested by existing literature. The reduction is computed only for the participants it would affect. Improving power management applies to Matt. Replacing desktops applies to Henry, Gary and Matt. Replacing large constellations, and feedback for engaged connoisseurs applies to Henry and Matt.

be high: the number of devices in these set-ups, and their role in multiple practices, makes user-initiated power management particularly problematic. For example, Matt relied on an always-on server to back up his laptop; a connected TV for video playback; and a connected stereo for TV audio and music. Reductions in direct energy through power management (contesting Chetty et al. [4]) are complex to automate, since devices can belong to more than one constellation. Power management strategies that respect constellations might aim to capture their context of use—the practices that they are supporting at a given point in time—e.g. sensing the power being drawn by individual devices, and/or sensing media and IT activities using software on smart phones, PCs, etc. The interpreted context could be used to ensure that only the required components of the constellation are powered up.

Streaming digital media presents a further challenge, since there is an inherent need for local infrastructure to enable on-demand services (e.g. wireless routers, cable modems); but also the not insignificant impact of the Internet and cloud service infrastructures that enable such services—which are equally (over-)provisioned for spontaneous use [10]. And yet, we note our participants' use of what could be regarded as legacy devices (e.g. media players, offline media), suggesting there is still a role for enjoying such things. Certainly, we would advocate that local storage and playback of content should be enabled as a default behaviour, even in network-enabled devices, potentially lowering their indirect impact.

Longevity and attachment

Another area of intense interest has been in the extension of IT device lifetimes as explored by Hanks et al. [11], with mobile phones being highlighted as notoriously short-life by Huang et al. [12]. Authors have envisioned longer lifetimes through: longevity in OS/app support [3]; or passing on the devices to others who would have otherwise bought a new phone [12]. For our participants this might lead to a small improvement (2% of embodied emissions). Replacing a laptop every four years is roughly six times as damaging as replacing a smartphone every year; so perhaps laptop, not phone, longevity is a more fruitful focus for HCI?

Odom et al. and Pierce et al. have extended this concept more broadly to consider lifetimes of all media and IT devices [15, 18]: if the devices seen in our studies were kept for twice as long (doubling their lifetime), this would reduce the embodied emissions by 18%. This is particularly significant for the connoisseurs that we saw in our study. Practices of connoisseurship usually entail frequent upgrading and replacing of devices with, typically relatively high embodied emissions, like televisions and games consoles. These inventories account for a disproportionately large share of the overall embodied emissions, supporting previous research on the need for better device longevity and attachment [**?**]. And the sharp variations in embodied emissions of different configurations (e.g. fig. 2), suggests the importance of carefully considering the particular devices and profiles of use, of design for longevity and sustainability.

But, depending on the usage and intensity of device configurations, longevity may not always be the most effective goal. For energy-intensive configurations with high use-time (e.g. Henry's in fig. 2), it might be more effective to replace a high-consumption constellation of devices sooner with more efficient alternatives, such as a laptop plus an Internet-enabled TV, or a single multi-function device such as an all-in-one PC. In a number of cases, a desktop or laptop was used to stream media and play back on an external display. An Internet-enabled or peripheral-enabled television might have saved 2.7% of the direct energy across all participants. Among 9 of our participants, we saw constellations of a TV combined with a games console and/or DVD player—this hints at some potential for integration of displays, games consoles, and media playback. Across all participants this might have resulted in an embodied emissions reduction of 5%, as well as likely direct energy savings.

There are also drawbacks to the degree of integration. All-in-one PCs tend to be replaced wholesale, since they tend not to be upgradeable in a modular way—for example, with a traditional desktop PC one might replace just the graphics card, or buy a new desktop but carry on using an older display. And particularly for connoisseurs, there is important meaning and satisfaction in acquiring used or new objects with enhanced functionality or aesthetics, and finding innovative ways to incorporate these into existing constellations.

The sharing of high-end (and usually high-impact) constellations, such as with group movie and game nights (Ian), or watching TV together (Donna), amortises the impact of these configurations to a certain extent, and clearly has additional meanings and significance for our participants. There are opportunities for designers to encourage shared use of media and IT devices in certain contexts, and even to think of more profound shifts from individual towards communal media and IT facilities, similar to those for laundry and cooking in co-housing communities.

We observed laptops and desktops implicated in very similar sets of practices: doing coursework, chatting with friends and family, social networking, reading the news, watching TV and listening to music. Laptops are designed to be mobile, so typically have lower impact attributes of fewer raw materials (less embodied emissions than desktops) and much lower power consumption as was evidenced in our energy data. Thus, at the point where a desktop might be upgraded or replaced, it can make sense to procure a laptop instead; across our particular participants, this might have saved 9.3% direct energy and 16% embodied emissions, even though it applies to just the three participants with desktops (Matt, Gary, and Henry).

Designing for connoisseurs

While appliance energy consumption typically has little relevance to peoples' everyday experience [19] and the effects of eco-feedback can be quite limited [22], there is also evidence that those interested in sustainable living or home automation engage well with and act upon information about appliance consumption [7, 25]. Our connoisseurs might be just such people; despite the high consumption overall of his devices, Henry made clear efforts to power down the constellation when he was away, and to turn off the corridor lights at night. If informed about the sources of direct consumption, Henry might have acted further to reduce it. Supposing Henry and Matt were to actively power down during idle times, this may have reduced the total direct energy impacts by up to 7%. But, being so invested in the nuanced properties of their devices, connoisseurs might also be interested and engaged with information about the total energy required by large constellations. Replacing their constellations with laptops (even high-end or gamer-tailored models) would have reduced the direct energy impacts by up to 40%.

CONCLUSION

Our UK undergraduate participants living in on-campus accommodation provide a highly situated, socially-specific view of media and IT in everyday life, and are not necessarily representative of other populations. However, we would stress that across these 33 participants, the 138 media and IT devices observed had highly varying levels of time-use, size, customisation, perceived qualities of service provision, and roles in practice. Our qualitative and quantitative 20-day snapshot of the variations in technology, practice and greenhouse gas emissions provides a new, informative basis for HCI researchers and practitioners to understand the range and nature of variations that exist with media and IT; and the fruitful (lower impact) directions to take future design, intervention and holistic impact enquiry.

Specifically, our more holistic account of the impacts (Figure 2) showed that the yearly carbon emissions arising from IT's direct energy are a *small fraction* of the emissions arising from manufacturing and transport (typically less than 20%). The important exceptions to this were the large constellations exhibiting long mains-powered durations, and/or had many of their interconnected devices powered up simultaneously (Figure 3). Compared to the total impacts of home media and IT across our studies, personal and wearable devices such as phones and tablets have very small embodied emissions (2%), and a vanishingly small direct energy demand (Figures 2 and 3).

Despite the fact that we observed remarkably similar sets of IT-supported practices among all 33 participants, we found that these were tied to very different sets of impacts. In our study, these large variations could in a few cases be attributed to specific hardware differences in similar devices: laptops which are easy to put to sleep, versus ones with faulty batteries. But for the most part, impact variation arose from *vastly different* capabilities and qualities in service provision: watching TV, surfing and writing essays on a laptop; versus the same practices carried out using a desktop connected to two monitors. The larger, more complex constellations had tended to be set up primarily for a specific purpose, such as gaming or listening to favourable reproductions of the latest music. However, the desktop PCs at the hubs of these customised constellations made them multi-purpose, resulting in exceptional durations of energy demand (Figure 4) temporally stretching well beyond the practices they were configured to support. As a result, connoisseurship presided over a share of about one-third of the total media and IT impacts in our study: 42% of the direct impacts, and 16.5% of the embodied emissions.

Media and IT connoisseurs can be challenging to sustainably design for: they have uniquely demanding, specific, and continually evolving expectations. The devices they pursue tend to have nuanced qualities in service provision (e.g. Henry and his audiophile speakers), and connoisseurs reconfigure constellations and apply upgrades, as they evolve in their role as enthusiast practitioners. However, connoisseurs present important opportunities for sustainability. They might adopt highly specialised, lower-demand devices much earlier than others. And, echoing prior empirical findings [7, 25], our connoisseurs tended to show more engagement and sympathy towards monitoring and managing resources; they might respond well to eco-feedback and act as local experts to help others do the same.

Our holistic framing has exposed some important avenues for future exploration in sustainable HCI. In particular, the impacts of the cloud's supporting infrastructure (large-scale networks and data centres) are not particularly well-understood, yet those impacts are strongly implicated in the always-on communication, information, and entertainment our participants had come to expect and rely upon across their devices. Frequency, bandwidth and durations of access to different cloud services need to be monitored and analysed, to understand how precisely these are called upon to support everyday life.

In our future work, we will be using analysis of home network data alongside associated carbon foot-printing of Internet based services (impacts of geographical location on the energy footprint of digital media [21]) to explore to what extent we can begin associating indirect carbon contributions with particular devices and practices, further filling in the holistic view of media and IT impacts.

ACKNOWLEDGEMENTS

This work was funded by the UK Research Councils (refs. EP/G008523/1 & EP/I00033X/1), and the Facilities Division and the Faculty of Science and Technology at Lancaster University. This work was supported by a PhD CASE studentship funded by the EPSRC and Microsoft Research. We would like to thank Mike Berners-Lee, Darren Axe, Candace Davies and John Mills for their ongoing cooperation in enabling our studies in student residences. We are grateful to Carolynne Lord for her significant contributions. Finally, we are grateful to our reviewers for their insightful comments and giving us the opportunity to improve this work for publication.

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