Exploring the Hidden Impacts of HomeSys: Energy and Emissions of Home Sensing and Automation

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Abstract

Home sensing and automation systems are rarely discussed with reference to their direct energy demand, much less other environmental impacts such as greenhouse gas (GhG) emissions arising from their manufacture and transport. It is imperative that designers of such systems understand the impacts of the technologies they introduce, particularly where intended to save energy and promote sustainability. Using four case studies drawn from recent Ubicomp and HCI literature, this reflective paper quantifies the direct energy and estimates the embodied emissions arising from specific installations of home sensing. We contextualise this by comparing with typical impacts arising from existing ICT devices commonly found in the home, and highlight a number of ways in which designers can reduce the impacts of the systems they introduce into the home.

Author Keywords

Home Energy, Home Systems, Embodied carbon

ACM Classification Keywords

H.5.m [Information interfaces and presentation]: Miscellaneous.

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Introduction

Much of the sustainability research in Ubicomp and HCI has focused on the study and reduction of energy directly consumed by appliances and infrastructure (e.g. HVAC) within the home. These efforts typically involve the deployment of sensors and supporting infrastructure including wireless networks, data logging servers and, in some cases, actuators such as motorised window blinds or remote controlled-thermostatic radiator valves. Researchers are quick to tout the potential savings arising from this new sensing and automation; less clear are the additional impacts arising from the introduction of the intervention itself. These impacts come in two forms: firstly, the home energy directly consumed to drive the sensing, logging, and actuation hardware installed; and secondly, and certainly more challenging to quantify, the greenhouse gas (GhG) emissions caused outside of the home by the 'embodied energy' involved in the manufacture, transportation and supply of the equipment introduced into the home. Awareness of these impacts are important, particularly since often a goal of these systems is to save energy or otherwise make life at home more environmentally-friendly. As a rule of thumb, the technology intervention should result in a net reduction not a net increase in energy and GhG impact!

Our analysis is grounded using case studies of four research deployments drawn from the Ubicomp and HCI literature. We start by characterising their direct energy (electricity) consumption. We then give a brief overview of relevant literature from the field of carbon life cycle assessment (LCA), which concerns itself with understanding and estimating the GhG impacts due to raw material extraction, processing, manufacturing and transport of complex goods (such as those commonly used in home sensing and automation). We then conservatively estimate the GhG that might be associated with the four deployments, alongside the impacts of the kinds of ICT commonly found in homes. Our analysis points to a number of ways in which home systems researchers might reduce the impacts of the systems they design.

Four deployments and their direct energy

The electricity consumption of deployed systems is relatively easy to estimate. Most mains-connected sensing and logging hardware can be observed to minimally draw a "baseload" amount of energy, with occasional 'spikes' when specific peripherals are utilised (hard-drive or networking, for example). We now describe four deployments which have been previously published, and estimate their direct energy impacts.

Using over 200 off the shelf sensors including per-socket energy metering, and associated data-logging PCs, Bates et al. [2] aimed to disaggregate direct energy use in 4 student flats, with the goal of understanding how services in the home contribute to whole home energy consumption. Clear et al. [4] studied the thermal comfort in 4 private student dorms with en-suite bathrooms. This deployment included door and window sensors, and per-socket energy sensors. Scott et al. deployed PreHeat [8], a system for home heating prediction and optimisation. House and Room units were custom built using Microsoft .NET Gadgeteer to sense motion and temperature, communicate with remote control thermostatic radiator valves, and communicate with a central home-gateway PC. Costanza et al. [5] deployed a single-point energy monitoring system and server, to actively engage participants in annotating, and hence understanding, their own energy usage.

These four deployments are summarised in table 1, alongside estimates of the direct energy used per day in each case. For the deployments where direct energy of the system itself was not separately measured [8, 5], we estimate using the hardware and operational descriptions provided by those authors, and by our own measurements of comparable system components.

Table 1: This table shows the estimated direct energy consumption, per day, from four studies in the home [2, 4, 8, 5].

	Description	Direct for a day (kWh)
Bates et al (2012)	per flat - 8 bedrooms, 1 kitchen. 41 per socket sensors, 9 motion/light sensors, 9 temp/hum sensors, 1 logging machine, 1 network switch	1.44
Clear et al (2013)	single private dorm room - 10 plug sensors, 1 logging machine, 1 network switch, 3 door/window sensors, 2 motion/light sensors, 2 temp/hum sensors	0.69
Costanza et al (2012)	whole home, single point electricity meter, media server/logging machine	0.42
PreHeat (2011) - UK deployment	Whole home - Prototyped sensors (3w), 1 per room (10), RFX Pulse sensor, RFXCom receiver, central server PC	1.24

Note that the direct energy arising from these deployments comes from the mains-connected devices—the Plugwise sensors used by Bates et al.; the Room Units in PreHeat; and the logging machines in all four deployments. It is important to note that although these are generally low power (nominally tens of Watts), they are typically *always active*, twenty-four hours per day— either by design (Plugwise sensors have no low-power mode), or because continuous measurement is required (logging machines must not miss sensor readings).

Embodied Carbon

To gain an idea of the embodied impacts of home systems we will draw on literature from carbon life cycle analysis (LCA) research. The LCA field deals with the estimation of GhG, and has a large focus on the embodied (indirect) effects of the manufacture and transportation of devices.

Due to the lack of transparency surrounding the extraction of materials, processing, manufacturing and transport, there are well known inaccuracies associated with the results of LCA. These inaccuracies are more predominant in complex products and processes (e.g. the manufacture of devices with a lot of integrated circuit boards). A review of a selection of LCA by Andrae and Anderson [1] offers insights into these inaccuracies (with a specific view on home media and ICT devices). Malmodin et al. [7] refers to previous studies on ICT kg CO_2e estimations and highlights how this lack of transparency in the surrounding processes of LCA leaves a lot of room for error in the calculated values. Bonvoisin et al. studies the environmental impacts of a city-scale wireless sensor network (WSN) [3], providing models, methods and tools that enable the assessment of the environmental impacts of WSN.

Teehan and Kandlikar [9] highlight a lack of LCA performed on newer ICT devices. To fill this gap Teehan and Kandlikar combine their own data from weighing individual components and using the ecoinvent database[1] to calculate values that represent the kg CO_2e created in the manufacturing phases of eleven post-2009 manufactured devices and three pre-2004 devices. Their results show that there has been a 50–60 % decrease in kg CO_2e produced between pre-2004 products and post-2009 products, and that this is due to more modern ICT products using fewer materials.

We have collated embodied carbon data from Teehan et al., whitepapers from Apple [2] and our own calculations into Table 2. We will use the value of 27 kg CO_2e per kg of mass for devices and sensors for which published (journal, whitepaper, or otherwise) LCA is not available. This value is taken from Teehan et al., *"Embodied impacts identified in our study are linear with respect to mass, with a coefficient of 27 kg CO_2e per kg of product"* [9, p. 4002],

Table 3 shows the total embodied carbon we have calculated for the four studies [2, 4, 8, 5], alongside two illustrative examples of typical media and ICT configurations that can be found in the home.

If any of the four studies that we have discussed were to be deployed in either of our 'Single Occupant household' illustrative example, between 20.2–43.8% would be added to the embodied carbon of the household. The 'more complex media and ICT infrastructure' example would gain between 9.8–21.2% in embodied carbon.

Table 2: Estimated embodied impacts for a range of devices and sensors that were observed in the four deployments [2, 4, 8, 5].

Device	Embodied Carbon (kg CO2e)	Source/Notes	
Mac Mini (2010)	194.4	Apple Tech report	
ASUS EEEBox (2011)	80	Small Desktop	Calculated using values from Teehan et al 2013
Desktop Tower	160	Desktop Tower	
Plugwise	2.997	-	
Network Switch	8.1	Includes power supply	
Motion/Light Sensor	3.24	Battery Powered.	
Marmitek Door/Window Sensir	2.16	Battery Powered.	
Oregon Scientific Temp/Hum sensor	2.619	Battery Powered.	
RFXCom Receiver (circa 2010)	6.75	-	
PreHeat Unit (.NET Gadgeteer--based)	10.8	Assumed embodied carbon if product was mass produced, includes weight of power supply.	
RFX Pulse Meter (circa 2010)	9.72	Includes power supply.	
Single point electricity monitor (e.g. Owl without display)	3.321	Battery Powered.	
HouseHeat HHFHT-8V	5.4	Battery Powered.	

Table 3 extrapolates the yearly total direct energy in kg CO_2e from the daily consumption in table 1. The yearly total is more relevant when considering long term deployments, (e.g. PreHeat is permanently deployed). If we compare the direct impacts of the four studies to our 'Single Occupant household' illustrative example, we see that the direct impact of any of the studies would increase by between 73–250%. The direct impact of the 'more complex media and ICT infrastructure' would increase by 19.8–67.8%.

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[1] `http://www.ecoinvent.ch/`

[2] `http://www.apple.com/uk/environment/reports/`

Table 3: The yearly impacts of several studies in the home against two illustrative examples. The illustrative examples' energy is based on detailed consumption data from similar appliances observed by Bates et al. and Clear et al.. We have used the Defra conversion factor adjusted to include Scope 3 emissions to calculate the direct emissions arising from electricity drawn from the UK national grid.

	Embodied Carbon (kg CO2e)	Direct for a year (kg CO2e)	Total (kg CO2e)
Bates et al (2012)	353.78	314.40	668.18
Clear et al (2013)	257.42	150.02	407.43
Costanza et al (2012)	163.32	91.98	255.30
PreHeat (2011) - UK deployment	258.47	270.68	529.15

Single Occupant household - 1 small TV, Laptop, wireless router	808.10	125.93	934.03
Household with more complex media and ICT infrastructure (1 large TV, 2 Laptops, 1 media server, wireless router, home cinema amp)	1668.10	463.92	2132.02

It is worth mentioning that the example PreHeat deployment shown is illustrative of a UK based deployment, in which there are radiators in ten rooms, all of which are remote controlled by wireless thermostatic radiator values (TRV). The wireless TRVs themselves add 54 kg CO_2e to the embodied carbon of this example deployment. In a typical US deployment, where there is central air controlled at a single point, the embodied carbon would be 204.47 kg CO_2e. It is also worth highlighting that the authors admit that saving electricity was not a focus in their work [8, p.3], and that if it had been, the Room Units could have been battery powered. This would have reduced the yearly direct consumption of our UK example by 157.68 kg CO_2e per year.

Discussion and Conclusion

Via our analysis of these four case studies, we have tried to make clear some of the relative impacts of home sensing and automation—both in the direct energy (consumed in the home) and in the embodied emissions (arising elsewhere during manufacture and transport). Table 2, in particular, details the estimated embodied emissions from some specific sensors and actuators. Other researchers might use these as rough indicators, to begin assessing the impacts of their own existing or planned deployments. But we can also draw some broader lessons, which have emerged by looking across the four case studies.

Piggyback on existing infrastructure and devices. Wireless networks, home media servers, laptops and smartphones are already present in many homes. Can these be utilised with careful alteration, rather than deploying new hardware and infrastructures? Can sensor data backups be stored on a PlayStation which powers up periodically? Can home energy visualisation and management be accessed via the occupants' own phones, laptops, or Internet-enabled TV, rather than installing a brand new display or tablet?

Combine devices and eliminate casings. Plastic and metal device casings contribute between 20–40% of the object's overall embodied emissions. Where possible, combine multiple functionalities into one casing (e.g. the PreHeat Room unit), or eliminate casings altogether.

Embedded rather than PC based logging. Computers designed to be always-on, like home media servers, are available which consume 10–20 W, a fraction of more traditional desktop workstations. But is it possible to lower power consumption by another order of magnitude? If a new data logger is required, then this might take the form of a lighter weight embedded computer like a Raspberry Pi. Peripheral (USB) flash drives can be added to such platforms, to provide ample storage for months of data collection. Many of these can connect to wired or wireless networks, so that daily off-site backups are feasible.

Single-point sensing. Our use of per-socket Plugwise sensors gave us good disaggregation [2], but the impacts dwarf those of deployments which use whole-house energy monitors [5]. Can signal processing be applied to a small number of sensors, rather than deploying sensors at every single appliance, fixture or tap [6]?

In general, the more sensing, logging, processing and control that we want to deploy, the higher the impacts. We would urge others to consider the impacts of the systems in question, held up against the expected energy or emissions savings which might be effected by the system. Even for a home with a relatively large number of ICT devices, the addition of home sensing can increase the emissions and energy by 10% or more.

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