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Categories and functionality of smart home technology for energy management

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ABSTRACT

Technologies providing opportunities for home energy management have been on the rise in recent years, however, it's not clear how well the technology - as it's currently being developed - will be able to deliver energy saving or demand shifting benefits. The current study undertakes an analysis of 308 home energy management (HEM) products to identify key differences in terms of functionality and quality. Findings identified opportunities for energy savings (both behavioural and operational) as well as load shifting across most product categories, however, in many instances other potential benefits related to convenience, comfort, or security may limit the realisation of savings. This is due to lack of information related to energy being collected and presented to users, as well as lack of understanding of how users may interact with the additional information and control provided. While the current study goes some way to identify the technical capabilities and potential for HEM products to deliver savings, it is recommended that further work expand on this to identify how users interact with these technologies in their home, in both a standalone and fully integrated smart home environment to deliver benefits to both homes and the grid.

1. Introduction

Technologies to support the development of smarter energy systems and enhance opportunities for home energy management have been on the rise in recent years [13,35]. Through the addition of sensing, communication, and actuation components, household devices and appliances are made "smart", such that they can communicate wirelessly with each other, transmit data to end users, and facilitate remote operation and automation, for example to reduce use during peak demand periods [64,73]. This has the potential to deliver energy related benefits to both end users and grid operators.

One major benefit of smart products is the potential to support energy reductions and demand-side management (DSM). For users, this can help deliver cost savings on energy bills, particularly in regions where time of use tariffs are present and load shifting would allow users to take advantage of cheaper time-periods for running appliances [43,58]. Utilities and grid operators have the potential to leveraging two-way communication with customers, facilitating real-time data transmission, enabling data analytics, and delivering greater control over power flows in the electricity network [53,78]. In addition to energy monitoring and cost savings, smart home technologies have the potential to deliver benefits such as convenience, control, security and monitoring, environmental protection, and simply enjoyment from engaging with the technology itself [27,28,50].

However, it's not clear how well the technology - as it's currently being developed - will be able to deliver on these benefits. The rapidly evolving market means that the functionality of smart home technology isn't entirely clear. There has been a lack of demonstration of energy and other user benefits in naturalistic settings, and the ability to deliver flexibility to the grid through demand side management has yet to be proven at scale in the residential sector [5,40,43,58]. This work therefore aims to explore the types and combinations of energy focused smart home

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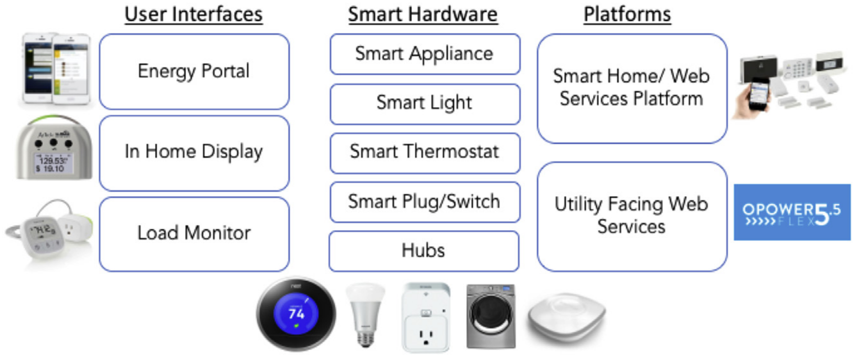

Fig. 1. Classification of smart home products [21].

products that exist on the market, and show how may they work to support user and grid needs.

2. Smart home products

While smart home products have been available since the 1980s [79], lack of powerful microprocessors, inadequate interfaces (touch screens become affordable only in the late 1990s) and high product cost, limited their market penetration. However, in recent years these products, which provide households with greater levels of information or control over their energy use, have received increased attention due to greater coupling of information and communication technology with electricity infrastructure through the development of smart grids [46]. Following smart meter rollout, products were developed to provide feedback to users about energy consumption of the entire house (through data collected from smart meters or specially designed sensors) or specific appliances [39]. These feedback products had limited connectivity capabilities and tended to reach consumers through utilities.

At the turn of the century, with new technology available, a few companies proposed new communication standards and created early “domotics[2]” consortia, mostly focused on automation, rather than energy management [33,81,82]. This enabled a second type of device, the connected thermostat, to be commercialised (e.g.: Nest [56] and Ecobee [15]) and marketed directly to consumers. These thermostats offered network connection, a remote smartphone interface and advanced control features. Connected thermostats became so popular that, after a few years, most thermostat manufacturers (e.g., [19,83]) had added at least one model to their offering. Since this time many other smart energy products followed, such as smart lighting, smart plugs and smart appliances. By 2015, trade shows and stores were flooded by hundreds of products produced by traditional manufacturers and new start-ups [21].

Early attempts of classifying smart energy home products were proposed by La Marche et al. [44] and Karlin et al. [39]. However, in recent years the market has seen much transition, with the emergence of many new products with increasing functionality, and the discontinuation of products popular just a few years prior [21]. In addition, software has become increasingly important in defining the features of these devices; as the number of products grew, it became clear that low interoperability was one of the major unsolved problems, and in response, several players started offering software and hubs to connect multiple devices under a single platform. The most recent attempt to classify these technologies and explore their capabilities (see Fig. 1) accounts for the dynamic nature of the market and the variety of hardware and software that may be used independently or together to deliver a smart energy home [21,41].

2.1. *Energy savings from smart home technologies*

The potential for energy savings and/or demand response associated with home energy feedback technologies (i.e., smart home products with information but no control capabilities, such as load monitors, web portals, and in-home displays) has been widely demonstrated [3,14,25,29,32,47–49,52,59,61,66,67,74,75,80]. Of all HEMS categories, in-home displays (IHDs) with whole home energy feedback but no control capabilities have been investigated the most in field studies, with energy savings ranging from none to 18% [3,29,32,49,52,61,67,80]. Studies of IHDs with demand response prompts have been found to be effective in shifting use from peak to off-peak times [48,66]. Most IHDs that have been studied are very utilitarian in design, offering text-based digital feedback, but more recent models include ambient feedback (e.g., colored lights) that some research suggests is more effective in promoting conservation [26] contribute to longer lasting effects.

Studies of appliance-level feedback, as enabled by load monitors and smart appliances, suggest it can yield savings from 12 to 20% [14,25,47,74,75,80]. In some of these studies, appliance-level feedback was provided for multiple appliances on a single interface at one time or offered in conjunction with an in-home display. Most were pilots of concept technologies developed specifically for the respective studies rather than products on the market, therefore little is known about the potential unique contribution of commercially available load monitors and feedback functionalities of smart appliances to energy savings. Sastry et al. [84] estimate the latter as 3-6% likely savings across smart refrigerator/freezers, clothes washers, clothes dryers, room air-conditioners, and dishwashers.

When the above smart appliances have been directly studied, it has been primarily in terms of demand shifting, rather than energy reduction, potential. A series of reports by public utility Southern California Edison [68,69] involved laboratory tests of smart appliance demand response (DR) potential. Findings include demand reduction of 100 W for a smart refrigerator during Spinning Reserve[3] events with demand reduction of approximately 100 W (W), but power increased a little during Delay Load[3] events [68]. SCE [69] also demonstrated that a smart dishwasher can achieve

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[2] Automation technology for homes; from latin “domus”: home and robotics.

[3] Demand response (DR) events are broken down into two specific types: spinning reserve if lasting less than 10 min, and delay load if lasting 10 min to 4 h [68].

demand reduction up to 1 kW.

Though some studies have quantified energy savings potential of smart lighting and plug strips in the commercial sector [2,22,24], less attention has been given to field-testing these technologies in the residential sector. A study based on simulations of residential buildings [8] suggests that CFLs coupled with smart lighting may allow up to 7% reduction of total electricity consumption at home, but they did not provide a statistic for the unique contribution of smart lighting to savings and their estimations were based on assumptions of user behaviour.

Smart thermostats have been a more popular topic of research lately. Several Utilities across the US have piloted smart thermostats in the last 4 years. These studies differ in methodology, brand tested, climate zone, size of the experiment and HVAC type, and are difficult to compare. Most of the studies show positive energy savings, but the range varies between -5% and +13% for heating and from 10% and 25% of cooling[4] [1,4,7,45,57]. Coupling these technologies with additional software to add intelligent learning or enable participation in demand response events can deliver greater savings. For example, EcoFactor [17] advertises that their Proactive Energy Efficiency Service saves 10-15% more energy than programmable communicating thermostats. Nest claims that their portal with demand response prompts, Rush Hour Rewards (RHR), has “helped achieve an incredible 55% reduction in energy use during peak times” [54].

In addition, many scholars project that HEMS savings potential is positively related to the degree of connectivity [71]. For example, Williams and Matthews [77] estimate that programmable thermostats save around 3%, whereas 26% can be saved with “an integrated system that includes monitoring and control of appliances, plus zone heating/cooling”; their estimates were based on data from the DOE Residential Energy Consumption Survey (RECS).

In conclusion, evidence for energy savings associated with HEMS control capabilities is building, especially for smart thermostats, but still very sparse [8,31,68,69,71,77]. Though promising, existing studies of the energy-related impacts of HEMS have rarely been conducted with naturalistic adopters in the residential sector. Much remains to be investigated regarding net energy impact of smart home technologies with HEM capabilities, both in terms of technical potential and what may be achieved in the hands and homes of consumers.

2.2. Smart home technologies and demand flexibility

In addition to energy benefits to households, new appliances may offer energy saving and shifting benefits to the grid. As energy generation becomes increasingly renewable across many nations the need for increased flexibility to cope with a variable supply side rises [30,34]. This flexibility could be provided by measures on the generation side (such as the use of gas peaking plants or overcapacity); by increasing the geographical footprint of the grid using long distance interconnects; through storage systems connected to the grid; or by demand side measures [6,23,63,70,72]. Currently underused, particularly in the residential sector, demand side measures have received large amounts of attention recently due to the emerging changes in household scale technologies such as microgeneration, behind the meter storage, and smart appliances.

Much recent work examining the technical potential for demand side flexibility in the residential sector relies on savings delivered via thermal and electrochemical storage. While the potential contribution from smart home technologies is both discussed in the literature and observed in field trials, there is a limited understanding around the extent to which these technologies are capable of delivering demand shifting and energy savings.

3. Current study

The current study aims to provide greater insight into smart home technologies that focus on energy management (home energy management, or HEM, technologies) currently on the market, explore their functionalities and review their potential to deliver benefits to users and the grid. This work uses content analysis to analyse data about smart home products, determine key differences within and between categories of technologies, and explore their potential for delivering energy savings and demand shifting.

A total of 550 individual HEM technologies were identified between November 2015 and April 2016. Descriptive data were collected and any technologies not matching the identified inclusion criteria were removed. A coding guide to support data collection was developed based on prior work and amended as needed during an iterative process. Data were analysed according to key themes identified from the codes as relevant based on prior literature and the objectives of this study. The following sections describe each of these processes in further detail.

3.1. Data collection

Data collection built heavily on prior work, drawing on work conducted by Karlin et al. [41]; in which 168 HEM technologies were identified. Four strategies were used to find additional products, including: (1) review of websites across key actors including retailers (e.g. Lowes, Staples), service providers (e.g. Comcast, ADT), and product manufacturers (e.g. Honeywell, Emerson); (2) Internet search of online markets for smart home products (e.g. SmartHome, SmartHomeDB); (3) lists from personal contacts, and (4) review of key media sites and newsletters focused on smart home technologies, including GreenTechMedia, Mashable, Techcrunch, Gigaom, the Northeast Energy Efficiency Partnerships, and CABA. This resulted in the identification of 550 HEM technologies.

3.2. Inclusion

This work defines HEM technologies as “those that enable households to more actively manage their energy consumption by providing information about how they use energy in the home or to prompt them to modify their consumption, and/or providing the household (or third parties) the ability to control energy-consuming processes in the home” ([40–42]: pp 17). HEM technologies fall into 10 categories as depicted in Fig. 1, including physical products with which users interact (sometimes via a software based energy portal) as well as software platforms that enable HEM technologies to be integrated into a Home Energy Management Systems (HEMS). Such systems include both hardware and software, linked through a network such that the information and control components communicate via this network and with the user through energy management software.

This work aimed to explore the energy saving and shifting benefits - to users and the grid - that could be delivered through HEM technologies, and therefore focuses explicitly on the hardware to deliver this. Thus, inclusion for this study stipulated that a HEM product:

1. Collects information about energy use or enables control of an energy consuming processes.

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[4] Percentages are relative to heating and cooling energy use and not whole-house energy consumption.

2. Provides information or control capabilities to users.
3. Is an actual physical product (i.e. not a concept or software only).
4. Has sufficient information available to describe the technology.
5. Is available for purchase and use within the United States.[5]

HEM technologies that met all five criteria were subject to inclusion. Of the initial 550 technologies identified, 308 products met all criteria and were included for coding.

3.3. Coding

Codes[6] were developed to systematically collect detailed data about each HEM product. Code development was iterative and utilized the constant comparison method and multi-phase coding [10,11]. Initial codes were developed based on previous literature [12,18,20,39,44]. Further variables relating to hardware, software, and communication capabilities were added to account for the physical and operational evolution of HEM technologies during the time since past work was undertaken. Additionally, to ensure sufficient data was captured to distinguish between the quality of similar technologies, the international Software and Systems Engineering standard 25010 [37] was reviewed to ensure sufficient data were captured related to product functionality (i.e. how it delivers information and control functionalities as well as non-energy benefits) and product quality (i.e. how well the technology meets its functional needs).

The coding guide was finalized following three rounds of iterative development, during which codes were tested against a variety of products and reviewed and amended as needed. This resulted in a total of 96 distinct codes. These were collapsed into 50 primary attributes by combining codes that represented multiple levels of the same characteristic (e.g., *iOS*, *Android*, and *Other, please specify* were combined as levels of the attribute *Mobile operating system compatibility*). The resultant 11 primary categories on which data were collected as shown in Table 1. The complete list of codes is presented in a companion paper [62].

Data were collected about each HEM technology following the coding guide. To overcome any subjectivity in the coding process, measures of inter-rater reliability were captured to ensure consistency [9]. Inter-rater reliability was acceptably high (kappa >0.700). To further ensure accuracy and consistency, the lead coder systematically reviewed the data across all variables. Despite this rigorous approach, data were not always available across every feature for each HEM technology; in some cases it was not obtainable and in others it was ambiguous. Under these circumstances the data were reported as missing.

3.4. Analysis

For each product category, all attributes collected were reviewed. Key characteristics relating to hardware (including sensing and actuation capabilities), communication, information (including feedback and prompts), control (both remote and automated), and benefits (energy savings and co-benefits) proved to be useful to characterize each product category. This information was also used to identify the main differences between products within each category in terms of both functionality and product quality.

4. Findings

The 308 products that met all inclusion criteria and were included for analysis were distributed across smart home technology categories identified in prior research [40–42] as shown in Table 2. Across the 308 products, 202 included an energy portal enabling users to interact with the technology remotely. Energy portals are provided via existing media channels, such as smartphone apps, websites, or computer software. Historically websites and computer software have dominated the market, but increasingly this is shifting into the mobile app domain; of the 202 energy portals identified, 190 work with iOS and 186 of these are also Android compatible (of the remaining 12 most lacked sufficient information to determine compatibility). Most of the 106 hardware only solutions that did not include an energy portal were designed to be incorporated into a third-party smart home software platform, and use the corresponding third-party energy portal to allow users to interact with the technology. The raw data analysed here is available in Ref. [62].

4.1. Load monitors

Eleven load monitors were reviewed, produced by 8 different manufacturers. Load monitors are hardware only devices; they do not have a corresponding cloud-based platform or web-based energy portal, and do not link into a third party smart home solution. Users plug an appliance into the load monitor's outlet, which measures and displays plug-level energy consumption.

Sensors embedded within the device collect data about the current consumed by the connected appliance. Of the 11 products reviewed, 4 also collect data relating to voltage levels, enabling accurate power readings to be provided to users. The remaining 7 estimate the power demands using anticipated voltage levels, which may not always be accurate.

Most products have a small screen embedded within the device, though this can make the information rather hard to view, especially if sockets are located near floor level or hidden behind appliances or furniture. Five products have cords such that the screen is more easily accessed, and one product communicates with its display using a wireless (rather than wired) connection. One product had no display and indicated an approximate power demand via lights, as depicted in Fig. 2.[7]

Load monitors display information to users using a numerical format; graphical displays are typically not feasible given the limited size of the embedded display. Across the 11 products the following information was provided: power (n = 11), energy (n = 9), cost (n = 9), carbon emissions (n = 5), current (n = 5), voltage (n = 4), power factor (n = 4), cumulative use/cost (n = 7), predictive use/cost (n = 3). This information stays on the device unless manually loaded onto a computer via a physical connection (e.g. SD card, USB key). Load monitors do not offer users advanced or remote control capabilities, although one product did include a built-in timer to enable users to manually pre-set a time at which the load monitor would shut off power to the connected appliance.

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[5] The study was initiated and funded by a California energy utility.

[6] Codes are variables that describe features or characteristics of the device. For instance, the compatibility of the device with the Wi-Fi protocol or the ability to measure temperature are two variables collected. In this context, code, attribute and variable are used as synonyms.

[7] Images were retrieved from websites during Apr-Jun 2016. From the left to the right:

Save A Watt, http://www.p3international.com/products/p4190.html.
Kill a Watt, http://www.p3international.com/products/p4400.html.
Belkin Conserve Insight™, https://www.belkin.com/conserve/insight/.
Kill a Watt CO2 Wireless, http://www.p3international.com/products/p4250.html.

Table 1
Primary attributes on which data were collected.

Coding Category	Purpose	Attributes[a]
1 Identifying information	To provide overarching information through which the product can be identified by future users of this information.	Developer/Make; Model; Version number; Date Coded; Cost to purchase; Cost of service; Functions lost with free service; Target demographic
2 Product components	To identify the various user facing smart hardware and interface components that are included in the product or product package.	Smart appliance; Smart thermostat; Smart lighting; Smart plug; Smart hub; In home display; Energy portal; Load monitor; Embedded Display, Main Category, Sub-Category, Short Description
3 Hardware	To define the hardware components of the HEM product that identifies how it delivers functionality. These features may also be used to distinguish between products in the same category.	Traditional Features; Sensors; Actuation capabilities; Power source
4 Communication	To understand how the product communicates and how it connects into part of a larger HEM ecosystem.	Product-system interaction; Hub/gateway requirements; Home WiFi network requirements; Communication protocol
5 Software	To identify which software platforms (smart home platforms and other supporting software platforms) the HEM product connects into to provide added functionality.	Smart home platform compatibility; Energy portal compatibility; Mobile operating system compatibility; Local interaction options
6 Information - Feedback	To provide additional information about the feedback functionality of the HEM product.	Feedback type; Predictive use; Comparison type; Electricity production
7 Information - Feedforward	To provide additional information about the information functionality of the HEM product.	Prompts/notification type; Advice type; Other information
8 Control	To identify how the HEM product provides control functionality to end users.	Remote control; Scheduled Automation; Rule-Based Automation; Learning; DR control
9 Utility interaction	To explore how the utility can interact with the system	Utility partnerships
10 Additional benefits	To identify whether the HEM product provides users with benefits in addition to energy management/cost savings	Fault detection; Convenience; Comfort; Safety/security
11 Usability	To explore how usable (plug and play) the product is	Installation; Removal; Support

[a] Also called code or variable in the section above.

Table 2
Distribution of smart home products.

Product category	No. of products[a]	No. of manufacturers	Information provided	Control provided
Load monitor	11	8	Real time feedback on power and energy	No
In home display	19	13	Real time and historical feedback on power and energy. Some also provide prompts for various events.	No
Smart thermostat	61	28	Real time feedback on setpoint and HVAC status.	Remote control via energy portal. Some allow users scheduling, rule based control, intelligent learning.
Smart light	56	15	Status of light.	Remote control (on/off) via energy portal. Some enable dimming, scheduling, rule based control.
Smart plug/switch	100	30	Some provide feedback on power use, others only on status of plug (on/off).	Remote control (on/off) via energy portal. Some enable scheduling, rule based control.
Smart appliance	30	9	Appliance status. Some also provide notifications to users about certain events.	Remote control (on/off) via energy portal. Some enable scheduling, rule based control
Hub	44	36	NA	NA

[a] The sum of products in each category in this table (321) is greater than the total number of product reviewed (308), because some products belongs to multiple categories. For instance, a thermostat can also function as a hub, or a lighting kit can include both the light source (smart light) and its connected hub. These products were included in both categories in Table 2.

Fig. 2. Differences between load monitor hardware.

Through the provision of energy feedback information, load monitors can support users learn about the energy demands of individual appliances. Given their portable nature, users can move the load monitor from appliance to appliance (rather than continuously tracking the use of one appliance), which may help increase awareness of how energy is being consumed across the home. This could lead to energy savings if users become aware of how they can minimise waste through changing the way they use their appliances, or replacing highly consuming appliances with more efficient models. However, the assumption that increased information and awareness about energy demands will lead to savings is problematic, given the large body of work showing that although there is a relationship between energy feedback and energy demand reductions, the variation in the effect is larger than the effect size itself [20,40–42]. Thus, while energy feedback provided by load monitors may help with some aspects of learning, additional support to identify and motivate appropriate action may be required. It is also unlikely that load monitors will lead to demand shifting or peak reduction because they do not track energy use over time.

4.2. *In home displays*

Nineteen in-home displays, produced by 13 manufacturers, were identified. These products collect data wirelessly from other devices in the home, and display information, such as energy use feedback or energy pricing signals, in real (or near real) time via a physical standalone display. One product communicates this data upstream to an energy portal so users can also access the information remotely, and three others, produced by the same company, provide PC software so the data can be visualised on a computer.

In home displays collect data from a variety of hardware. Most ($n = 10$) connect directly to the smart meter, two connect to optical sensors added to traditional meters, five get data from current transformers that either connect to the main meter or to sub circuits on the distribution board in the home, one gets data from Insteon smart hardware, and one gets data from its corresponding load monitor. All in home displays show real time (or near to real time) data about power demands and/or energy use of the connected device; many also provide cost and carbon comparisons. Of the 19 devices identified, 17 provide historical use data, and 6 display predictive use. Nine also provide prompts about demand response events ($n = 7$), target budgets being reached ($n = 4$), or custom information as requested/set up by users ($n = 2$). None enabled control of any connected device.

As with load monitors, in home displays can help users learn about the energy demands of their home. Because the information provided is typically at the whole home or circuit level, and because it is provided historically over time (as well as in real time), these products may better support tracking (e.g. monitoring ongoing energy use) than learning (e.g., gaining specific information about energy use) functions of feedback [38]. However, they do not provide any direct load control, and savings are most likely through induced behaviour change resulting from an increased awareness and understanding of demand. The demand response prompts provided by a number of the in home displays can also support users to load-shift through behavioural demand response programmes.

4.3. *Smart thermostats*

Sixty-one smart thermostats were reviewed, produced by 28 different manufacturers. These products build on the capability of programmable thermostats, which incorporate on-board schedules whereby users can set a variety of time points with different setpoint temperatures, enabling energy savings by reducing heating and cooling loads at times of the day when it is not needed. Smart thermostats go beyond this, using a communications protocol so that users can view and adjust their settings remotely via a compatible smartphone app or website. It is embedded sensors, actuation capabilities (i.e. the physical control mechanisms), and communication that make a thermostat “smart”.

In addition to temperature sensors (which all thermostats have), many also collected the data related to humidity ($n = 18$), occupancy ($n = 5$), light level ($n = 1$), and outdoor weather ($n = 4$). Some thermostats also came with remotely connected sensors, which could be placed in additional rooms in the home to determine temperature and occupancy in multiple rooms. These on-board or remotely connected sensors can trigger a reaction in the thermostat; for instance, when the house is unoccupied the thermostat can revert to “away” mode, using energy-savings setpoints. Some smart thermostats also aim to optimise heating and cooling energy demands using machine learning algorithms. Advanced control algorithms for thermostats have been developed by academics for several years [51,60,65,76] and have recently been incorporated into products [15,16,55]. Most of them rely on models to predict future behaviour of occupant comfort, energy use and/or occupancy in a house, based on control decisions, weather and other inputs. These models are used to calculate alternative scenarios and choose the control action (e.g., whether to use one or two stages of heating) that optimizes an objective (generally minimizing energy use). These models are pre-programmed into the products, but their coefficients are learnt from real data of the specific house. The initial training period varies from a few days to a few weeks depending on the complexity of the model.

Across the 61 products, three subcategories emerged. The first, “communicating programmable thermostats” ($n = 3$), are a simple evolution of the programmable thermostat, whereby products communicate with utility servers, allowing them to be controlled remotely and participate in demand response programmes. However, they tend not to provide an energy portal for customers to access the device remotely, so from a consumer perspective communicating programmable thermostats offer few additional “smarts”.

Thermostats in the second and third subcategories provide households, as well as utilities, advanced information and/or control functionality. The key difference between the second category, “hardware only thermostats” ($n = 24$), and the third, “standalone thermostats” ($n = 34$), relates to how they are packaged and sold to consumers. Hardware only thermostats, as the name suggests, does not include a native software platform or energy portal. Instead, the thermostat is sold as a component of a larger smart home system rather than a standalone product, in which it communicates to the third party smart home software platform via a hub. Standalone thermostats, on the other hand, can operate as independent products, which typically communicate with their native software platform and energy portal via Wi-Fi direct to a broadband router. Some standalone thermostats also play the role of a hub (e.g. Nest), setting up a home area network (HAN) to allow other devices to connect into a smart home platform. These interactions are shown in Fig. 3.

In terms of energy feedback, all devices presented real time data on setpoint and HVAC status, though only a few store historical use data. None provide information about the power demands of the connected HVAC unit, though runtime is frequently reported as proxy for energy use. Some provide additional features such as the prediction of energy use based on modelling, usage comparisons to peers, notifications when problems with the system emerge, and energy advice.

The main benefits from smart thermostats is the ability to remotely control temperature setpoints and modes (heat, cool, auto, off) via the energy portal. Some energy portals also allow users to view and modify setpoint schedules, and for 11 thermostats this is the only way that users can adjust the schedules (i.e. they cannot do this directly in the device, but have to interact via the app). Some thermostats enable users to set rule based control, for example, changing the temperature setpoint if rooms become unoccupied, if energy costs increase, if the weather forecast changes, or if people are coming home. Others include “intelligent” learning, for example, the Nest adapts setpoints according to

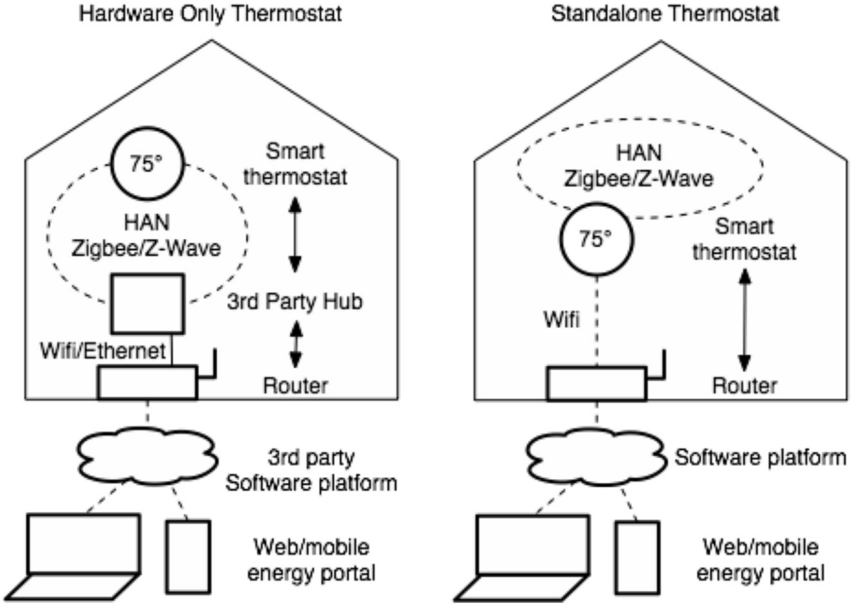

Fig. 3. Smart thermostat-system interaction.

learned occupant behaviour.

Of all the smart home technologies, the energy savings potential associated with smart thermostats is perhaps the most obvious given the high heating and cooling demands in many climates. While little (if any) feedback about heating and cooling use is provided to users, opportunities for increased user engagement with heating and cooling control via the energy portal may stimulate savings through behavioural changes, particularly if supported by notifications, prompts, or energy advice. Automation options provide another route to savings through adjusting control to set back temperatures when rooms are unoccupied. Further savings are possible using machine learning algorithms that learn a household's temperature preferences and ensure these are met while optimising efficiency of operation. And the collection of third party data, including weather forecasts, can support further insight around demand needs and help reduce waste.

Pre-heating or cooling through demand response programs can help shift the time of operation, resulting in whole of system efficiency gains, and carbon and cost reductions. Ten of the thermostats reviewed were able to display pricing signals or messages from the utility, enabling users to adjust their setpoint accordingly. Another 16 are able to receive a signal from the utility to participate in a demand response directly, though users are typically able to set preferences around participate and override signals for comfort related or other preferences.

4.4. Smart lights

Fifty-six smart lighting products were reviewed and coded, produced by a total of 15 separate manufacturers. Smart lights incorporate sensors, microprocessors, and remotely controllable switches or relays into traditional lights, which can offer users remote or automated control functionality (e.g., scheduling, occupancy control, daylight harvesting).

All smart lights used LED bulbs, and primarily used industry standard fittings ($n = 44$) that could easily be substituted into existing plug sockets. In addition to these, the research identified 4 light strips, 2 strings with multiple small led bulbs for outdoor lighting purposes, 3 portable lights comprising bulbs and batteries housed in a aesthetically designed shaped for indoor and outdoor mood lighting, and 4 mixed use products (e.g lamps that house other products, such as audio speakers, cameras, wifi boosters etc.). Of the 56 products, 49 were sold as individual light sources (costing between $15 and $150) and 7 as starter kits (typically comprising 1-2 lamps and a hub, costing between $50 and $100).

No lights measure power consumption, and focus more on providing advanced control to users; information tended to mainly show the status of the connected light (i.e. whether it's on/off or set to a particular colour or dim level) to support control functionality. All smart lights enabled remote control via their connected app, 16 offered dimming options, and an additional 21 offered both dimming and colour changing options. Some allowed users to cluster bulbs into groups and control the group of lights with a single command. Forty-eight allowed users to automate the operation of the lights, for example, setting a sleep mode during which lights dim gradually or pre-setting schedules for turning on and off, and 44 enabled rule based control, for example, using platforms like IFTTT (If This Then That) to set lights to turn on or off in response to events such as users' phones detected as being close to home. None included learning algorithms for more intelligent control options.

The energy saving potential of smart lights isn't entirely clear, given that their value proposition tends to focus on delivering additional security through remote or autonomous control to simulate occupancy, on added comfort and convenience through the use of automated dimming when going to sleep or waking up, and on fun and playfulness with colour control. However, if used to replace non LED light sources then there is a clear energy efficiency gain, and additional benefits may arise through more tightly control use of lighting that better matches room occupancy with lighting needs, eliminating over-illumination and unnecessary usage.

4.5. Smart plugs and switches

Fifty-six smart plugs and forty-four switches were reviewed, produced by a total of 30 manufacturers. These products sit between the electricity source and appliance, providing information and control functionality to non-smart appliances. The main hardware variation between products related to whether they were portable plug sockets that could be moved from location to location, or whether they were intended to replace existing outlets. While all products enabled connected devices to be toggled on/off, 26 also offered dimming functionality to support lighting control (see Fig. 4).[8]

Forty-three products collect data on power use (instantaneous and historical) to provide to users via a connected app, while the remainder only provided information about the status of the connected appliance. As with smart lights, the main focus of these products is on providing advanced control to users. Almost all enable remote control, 60 also allow users to set time based automation schedules, and 14 provide rule based control, for example, using power sensing to minimise standby power demands, or via IFTTT to respond to external triggers.

If used appropriately, smart plugs and switches offer potential energy saving benefits, for example, through reducing the demands of appliances that are always on (e.g. routers, TV boxes) when they are not needed. In addition, users with time of use electricity tariffs, or those participating in behavioural demand response programs, may be able to leverage smart plugs and switches to control connected appliances accordingly, reducing their use at peak times.

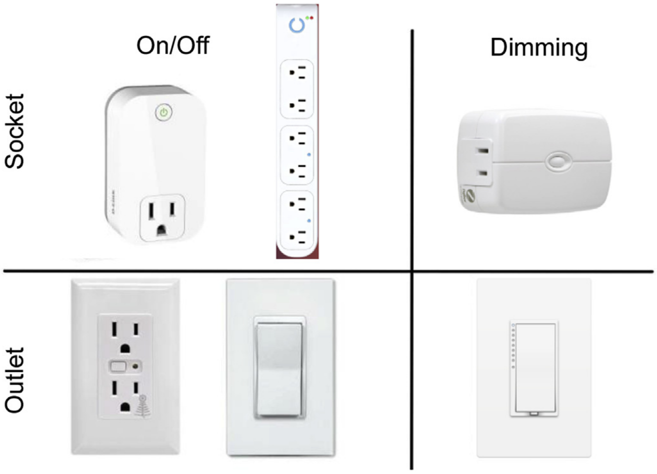

Fig. 4. Sub-categories of smart plugs and switches.

4.6. *Smart appliances*

Thirty smart appliances were reviewed, produced by a total of 9 manufacturers. These included both large and small kitchen/utility appliances ($n = 19$) as well as HVAC focussed appliances or appliance components (e.g. humidifiers, heaters, adjustable vents). Smart appliances differ from standard appliances in that they incorporate additional sensors and actuation capabilities to provide users advanced monitoring and control capabilities to improve operation. However, only 8 of the thirty smart appliances included sensors to collect data about power consumption (including two washers, two dryers, two refrigerators, an oven and a dishwasher). Six collected temperature data, 3 humidity, 1 motion, and 1 air pressure (all were HVAC related appliances or components). Additionally, 23 collected data on their own operation, including HVAC fan speed or status, filter life, rinse agent status, operation completion, internal moisture temperature or pressure.

Most smart appliances engage users through a connected energy portal, usually an app on their smartphone. Typically the information provided to users relates to the appliance status, for example, oven or refrigerator temperature, washing machine cycle status, or humidifier current and target humidity levels. However, those appliances measuring power also provide feedback on energy use. Nineteen of the smart appliances also provide prompts to users, such as notifications when the laundry has finished or when it's time to change the air conditioner filter, and four provide energy advice around when to use the appliance based on time of use rates.

All 30 appliances allow users to remotely control them via the energy portal, turning them on and off, setting specific models, and changing parameters such as temperature setpoints. Fifteen also allow users to set schedules, and 14 allow for rules to be set to govern operation, either via platforms like IFTTT or through connecting to a Nest thermostat (if users have one) to take advantage of information on household occupancy.

While smart appliances could offer energy saving opportunities to users - for example, encouraging them to set more economical run cycles on the washer/dryers, or adjust setpoints on thermostats - it's not clear that this function is highlighted for most of the appliances reviewed. The increased information to users via an app may encourage or enable them to control their appliances in a more efficient manner, but very few products provide explicit links between operation and energy demand.

The additional sensors embedded in smart appliances to support optimal operation (e.g. fan speed, filter life, internal temperature) may enable appliances to run more efficiently, reducing waste associated with operation. And for HVAC appliances, the use of fans and humidifiers can support the distribution or quality of air in a room and remove the need for additional heating/cooling due to stratification and vents can save energy by closing airflow in rooms that are not being used.

There may also be opportunities for smart appliances to support users with load shifting, for example, to participate in time of use tariffs. Because they can be controlled remotely, users can set appliances to run for off-peak times that may be convenient, but which would otherwise not be possible to set (e.g. because of limitations around manually set start delays). Temperature setbacks can also be made for shorter time periods, for example, critical peak pricing or demand response events.

4.7. *Hubs*

Hubs have become increasingly popular in recent years, largely due to the lack of a single communications standard across the smart home space. As a result, products are being developed that are not capable of communicating with one another; hubs can help overcome part of this communication barrier by creating networks to which multiple different smart home products can join.

We reviewed 44 hubs, produced by 36 different manufacturers. Hubs operate by decoding networking protocols[9] from one product,

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[8] Images were retrieved from websites during Apr-May 2016. From the upper left to the lower right:

1. D-Link DSP-W110 Wi-Fi smart plug, http://shop.us.dlink.com/shop/shop-automation/smart-plugs/d-link-dsp-w110-wi-fi-smart-plug.html.
2. Aeotec smart power strip, http://aeotec.com/z-wave-power-strip.
3. Ezzigbee plug-in dimmer, http://www.ezzigbee.com/plug-in-smart-dimmer/.
4. Ezzwave in-wall smart outlet, http://www.ezzwave.com/in-wall-smart-outlet/.
5. Enerwave zwave smart switches, http://enerwaveautomation.com/product-category/z-wave-switches/smart-switches-z-wave/.
6. Insteon dimmer switch, http://www.insteon.com/wall-switches.

[9] As defined in the Open Systems Interconnection model [36].

wrapping the information inside in another protocol, and sending it through a different network, so that devices that speak different "languages" can communicate with each other and to a smart home software platform via the Internet. The "network hub" enables smart products to connect to a HAN by translating one protocol into another. 33 products of this kind were found in our review. Some of these hubs can only translate a single network protocol in addition to the wired (e.g. Ethernet) or wireless (e.g. Wi-Fi) protocols they used to connect to the home router and send data to the cloud. These hubs provide a HAN gateway for smart lights or smart meters and are the least expensive. Other network hubs speak multiple protocols and connect a variety of smart hardware: thermostats, lights, appliances and other non-HEMS devices. They are two to three times more expensive than the first subgroup. "Intelligent hubs" include 11 products that have a more powerful processor and memory and effectively act as small computers – of the 1 GHz, 1 GB ram/HD scale – running an operating system such as Linux, Android or Windows (e.g. CastleOS; a full computer running Windows 10 and dedicated scripting language to write rules). Some intelligent hubs perform additional computation and enable functionality, such as rule-based control, to be implemented locally. This can also allow energy portals to directly control devices in the home without having to communicate via the cloud, i.e., avoiding delays in communication. The two most common protocols used by hubs (excluding Wi-Fi) are ZigBee ($n = 28$) and Z-Wave ($n = 11$).

While hubs offer no energy savings potential of their own, they can support the development of a more fully integrated smart home solution through enabling additional communications between products, and this is suggested to be positively related to overall savings potential (e.g., [40–42,71,77]). In addition to savings that may be obtained through the use of smart home technology, an integrated system may deliver benefits through the sharing of information between products. For example, it may enable smart products to access data from occupancy sensors belonging to another product, and adjust their operation accordingly. While this might also be facilitated via software (e.g. through platforms like IFTTT), hubs can enable some control to be implemented directly within the home, rather than relying on data to be sent to servers, processed, and returned again before implementing action. Thus, while hubs are not directly of particular when thinking about energy savings, their role in creating a smart home environment could be critical in leveraging greater savings across connected hardware.

5. Discussion

Across the products, there seems to be a split between those with a strong focus on delivering energy-related information, and those that provide advanced control functionality, often with a focus on comfort, convenience, and security rather than energy, but with the potential to deliver energy-related gains through increasing operational efficiency or enabling load shifting. Table 3 provides an overview of the energy saving opportunities for each category of smart home technology.

Load monitors and in-home displays have the strongest focus on delivering energy feedback to users. Load monitors provide immediate information relating to power and energy demands, but most do not deliver any historical feedback. While this may help users to learn about the energy demand of individual appliances, the lack of historical information prevents them from seeing trends in operation. Further, the location of the feedback at plug level makes it difficult to investigate the energy demands of larger appliances that are wired in, or whose plug sockets are not easily accessible.

This could limit the use of load monitors to easily accessible appliances, such as consumer electronics or small kitchen appliances, which may offer less potential for delivering energy savings. In-home displays provide both immediate and historical information about power and energy use, but tend to be at the whole home level rather than for individual appliances. While this type of information can help users to track consumption patterns, particularly for higher power or energy-consuming appliances, it is limited in terms of supporting users to identify faults or opportunities for savings.

Despite the wealth of research into energy feedback (e.g. Refs. [12,18]), little is known about how and for whom feedback works best, largely due to methodological design issues and use of non-naturalistic settings [40,42]. A better understanding of how users might interact with these devices in the context of a smart home setting would drive further insight into how they can support energy savings and load shifting.

Most of the other products (thermostats, lights, plugs/switches, and appliances) provide limited or no feedback related to energy use. With the exception perhaps of smart thermostats, they are largely focused on delivering other values, for example, colour-changing lights that provide ambiance (comfort) or that can give the appearance of an empty home being occupied (security), or smart washing machines that can be timed to finish when someone is returning home (convenience). While some of these technologies may deliver savings through operational efficiencies, there is the potential that these other values conflict with energy savings opportunities, resulting in increased load, for example, smart dryers running programs that reduce creasing in clothes by cycling operation until users return home. These products also provide limited capacity for delivering demand side flexibility, and while some work suggests that users may take advantage of smart devices to shift their activities (e.g. when they do their laundry), most products are not set up to facilitate this sort of interaction.

Smart thermostats do have a stronger focus on energy savings and shifting potential, particularly through the use of intelligent and rule based-control, and their ability to automatically participate in demand response programmes. However, the actual savings or shifting potential is dependent on how users interact with these technologies, and there has been limited research in this space. For instance, it is not entirely clear what the value proposition of shifting demand is to users; if smart home technology wants to leverage demand shifting then understanding these values, and figuring out how to easily incorporate into product operation and control, is key.

While customers may cite energy management and cost savings as motivators to adopt smart home technology, it is more common to see purchase dominated by values related to protecting the safety of one's household, and values related to fostering a nurturing home environment [21]. There has been little evidence into the demonstrated savings potential and energy consumption implications of smart home technology in the real-world context (as opposed to the lab), and this would be worth investigating further to explore the true energy consumption impacts on demand.

5.1. Limitations and next steps

While this work provides one of the most comprehensive assessments of home energy management technology to date, it nonetheless drew boundaries for guiding data capture. The focus was limited to consumer-facing technologies that fell into the previously identified categories (load monitors, in-home displays, smart thermostats, smart lights, smart plugs/switches, smart appliances, and hubs) and which were available for purchase and use in the US. This presents a number of limitations.

First, many smart energy home technologies are targeted

Table 3
Potential savings from smart home technology.

Product Category	Energy Savings		Load shifting
	Behavioural	Operational (automation & increased efficiency)	
Load monitors	Energy feedback about individual appliance use may increase energy literacy and lead to changes in use of appliances and savings.	No automation of control functionalities. Energy efficiency may be achieved by behavioural change.	No automation of control functionalities. Energy efficiency may be achieved by behavioural change.
In home displays	Energy feedback may help households understand patterns of demand and lead to changes in use of appliances and savings.	No automation of control functionalities. Efficiency may be achieved by behavioural change.	No automation of control functionalities. Load shifting may be achieved by behavioural change.
Smart thermostats	Limited feedback about energy use. Ability to remotely control and set schedules for temperature settings may lead to savings.	Intelligent learning algorithms and use of additional sensor data (e.g. weather, occupancy) may drive operational efficiency gains.	Remote, scheduled and rule based control enables users to adjust operation in response to demand response signals. Some respond directly to signals from utility.
Smart lights	Limited feedback on energy use. Ability to remotely control and set schedules for lighting may help reduce use and enable savings.	Potential gains through replacement of traditional or CFL bulbs with LED bulbs.	Limited opportunities for demand shifting.
Smart plugs/switches	Half provide energy feedback which can support energy literacy gains and lead to savings. Remote, scheduled, and rule based control may help reduce use of connected appliances.	Limited; one product works to reduce standby power of connected appliances,	Remote, scheduled, and rule based control allows users to adjust operation in response to demand response signals.
Smart appliances	Limited feedback on energy use. Limited behavioural savings potential through remote, scheduled and rule based control.	Many smart appliances operate at greater efficiency levels than traditional counterparts, enabling operational gains.	Remote, scheduled, and rule based control allows users to adjust operation in response to demand response signals.
Hubs	NA[a]	NA	NA

[a] In this review, hubs are considered enabling technology for HEM, supporting communication and data sharing between devices. As such, no savings are directly attributed to them. However, connectivity between devices can be positively correlated to potential savings [40–42].

toward utilities rather than consumers. These technologies tend to have more of a software than hardware focus (e.g., they provide platforms to enable advanced consumer engagement, demand response and/or data analytics), though some do also interact with consumer-facing smart hardware, for example, through demand response programmes. Unlike most consumer-facing products, these solutions are almost exclusively focused on delivering energy benefits, however, limited information is available online pertaining to their capabilities, and they are often white-labelled and tailored for different utility clients. Further work should consider how these solutions may interact with and form part of the smart home environment.

The second limitation is due to the rapidly evolving smart home landscape. Between prior work undertaken in November 2014 [41] and the current study, 73 of 168 home energy management products disappeared from the market, and another 119 were introduced. In addition, new products have come into the market that would not be considered as having a home energy management focus (and therefore not included in this work), but which would interact significantly with a smart energy home environment. For example, voice activated controllers such as the Amazon Echo or Google Home, were not included in this work, but likely impact the way in which households interact with and use products that are of interest to this study.

This raises a third limitation of the current study, which is related to the exclusive focus on product capabilities as identified via online search. This work ignores user interaction with smart energy home products, though our findings suggest that this component may be precisely what determines the extent to which smart technologies deliver energy related benefits. Further work should aim to explore user interaction with these technologies in naturalistic settings to identify the actual opportunities and benefits they bring to households. A set of studies should investigate how people use HEM products at home, capturing user interaction, values pursued, common routines and other behavioural elements influencing energy consumption. An interesting idea would be exploring the use of newer devices, such as automated personal assistants (e.g., Apple Siri or Amazon Echo), that make interaction easier. Follow up studies should quantitatively compare the actual energy use of houses with HEM technology with that of houses that do not use it. However, the literature shows that such field tests are difficult to generalize, due to differences in household demographics, occupant schedule, consumption patterns and climate [1,4,45,57]. In addition, most of the devices reviewed, except for smart thermostats, use or control a small amount of energy, requiring expensive and intrusive sub-metering to detect differences between households.

Finally, while this work acknowledges the importance of products such as hubs for facilitating an integrated smart home environment, the research focuses on the capabilities and energy savings potential of individual products. However, working together may enhance the operation of smart home technologies, and offer further value to households. In future, it would be worth extending such an analysis beyond individual products to explore the opportunities from connected smart energy systems and product bundles.

5.2. Conclusion

The aim of this paper was to explore the range of home energy management technologies on the market, and identify how their functionalities may support energy reductions and load shifting opportunities. Cataloguing and analysing individual the product landscape is a key step to understanding and leveraging their use for energy efficiency and demand response. The current analysis presented information on 308 HEM technologies across 11 product categories and coded them on 50 key attributes, thus significantly increasing our understanding on how HEM technologies can currently be leveraged for energy savings.

While it is clear that there are opportunities for products to help users manage home energy use, their full potential may be limited by a lack of information related to energy, conflicting value propositions resulting in the increase in energy use in order to make homes more secure and comfortable, and minimal interactions with demand shifting programmes. The true potential for demand side flexibility will be driven by how users interact with these products. Future research should identify how home energy management technologies are implemented in homes, and explore how the addition of prompts, incentives (e.g. through time-of-use tariffs), and easy to implement rules (e.g. automating appliances to reduce operation when time-of-use electricity prices are high) can help stimulate further benefits to both users and the grid.

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