Pitfalls and Potentials of Home Energy Monitoring Feedback: An Information Experience Critique

Marlen Promann[1,2], Zhenyu Cheryl Qian[1(✉)], and Yingjie Victor Chen[2]

[1] Interaction Design, Purdue University, West Lafayette, USA
{mpromann,qianz}@purdue.edu
[2] Computer Graphics Technology, Purdue University, West Lafayette, USA
victorchen@purdue.edu

Abstract. Our ageing energy grid, the fundamental resource for human activity, remains one of the great societal challenges. Governments and the energy industry are visioning a future of an engaged society that sustainably produces and consumes energy via a shared multi-directional Smart Grid. This vision; however, depends on our current efforts to increase public's awareness and comprehension of energy as a limited consumer product, involving personal choice. Energy monitoring and feedback, along with home automation, are fast emerging markets to support this vision. We reviewed 75 currently available home energy-monitoring systems (HEMS) and discussed their pitfalls and potentials. We hope to encourage discussions about the role user experience design could play in personal information visualization, and in addressing fundamental societal problems. We call for experience centric explorations into HEMS' design to address the energy feedback needs of the future.

Keywords: Home energy monitoring · Eco-feedback · Information displays · User interface · Information visualization · User experience

1 Introduction

The current usage of limited natural resources (e.g. coal, oil and natural gas), rising concern over global warming, steadily increasing energy demand, and ageing power grid hardware, all pose significant concerns on our ability to sustain our current ways of energy consumption [1]. In the United States, one of the largest energy producers and consumers energy demand is expected to grow 30 % by 2030, but our ageing grid structure, suffers increasingly from outages, costing $500 per person per year [3].

In an effort to avoid a sustained crisis in the long run, world governments have been seeking for feasible and effective ways to incentivize demand for renewables [3]. The lack of user awareness and comprehension of energy is the key roadblock in engaging people to care for the public good. Besides choosing a utility provider, people have had no avenues to get involved with the energy industry. Utilities have offered little feedback and so, little reason for users to be interested. This is persisting against the emerging findings, that people who live in eco-developments perceive their life quality and happiness higher than residents of traditional developments [4].

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A new global market for home energy management systems (HEMS) has emerged with a 27 % growth rate [5]. The traditional heating, ventilating, and air conditioning (HVAC) or advanced central controllers, are complemented with smart thermostats, HEMS and automated monitors that form increasingly automated ecosystems that talk to each other over the Internet.

HEMS are important because their real-time feedback has the potential to increase awareness via self-reflection, and their two-way communication with utility providers can empower users to help manage the energy load in the Smart Grid. In-home displays used to function as the important feedback loops for HEMS; however, the physical displays are disappearing into clouds, accessible via third party smart devices [6]. New ways are needed in which to think about personal data visualization in users' casual home environments. We discuss the limitations of the current feedback solutions and call for new user experience centered information designs.

2 The Problem

Utilities and grid operators have argued for years that it is necessary to reduce peak consumer usage to ease the operation costs of the U.S. power grid [7]. Current energy demand response programs, that is, "*changing electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized* [8]", while limited, are the starting-point for this vision of real-time multi-directional energy platform. HEMS function as the gateway for this real time communication between the demand and the supply. With more than a half of the U.S. population (66 %) unaware of what the Smart Grid even is, the challenge of how to bridge the gap and engage users in this communication, remains.

For decades, studies have reviewed behavior change literature and the adoption of feedback technologies to identify pro-environmental behaviors and to understand what incentivizes people [9–11]. The national energy labeling program 1992 in the U.S. proved influential on purchasing decisions, but only when consumers comprehended their meaning and impact on their life [12]. It worked, because it was added value at the point of purchase. The home energy consumption is not as susceptible, because it is not a conscious purchase decision.

Mechanisms that have repeatedly shown to deliver desirable results include: goal-setting, commitment, cognitive dissonance, and financial rewards, none of which grant perfectly positive results [10]. Discount price and savings-based incentives seem to be the most reliable ways to encourage behavior change [13], reported to save households between 5 and 15 %. The resulting argument that real-time energy consumption feedback will motivate users to change their behavior is certainly true in some, mostly experimental settings. The life context presents many more barriers, including users' state of mind, other cost variables, ease of use, and design [11, 12].

Despite the fast growth of the HEMS industry, the energy consumption feedback (i.e. feedback displays) has not become compelling enough to get past the tipping point in market adoption [14]. Given their mediating role between demand and supply of the energy grid, exploration into their limitations and potentials is required [15].

With the proliferation of HEMS in the market, a number of reviews have compared the product and technologies [11, 16], evaluated their functionalities [16, 17] and feedback capabilities [11, 15]. The needs for easy interface access, good aesthetic quality and enjoyability have been noted, yet no review has focused on the interface details. We set forth to study the data presentation features of HEMS' feedback and evaluate their limitations and potentials against the future energy vision.

3 Method

To understand the strengths and weaknesses of current HEMS' feedback displays, we reviewed the feedback interfaces of currently available HEMS products and software. We used Google's Chrome web browser to conduct two searches: "home energy monitoring" + "product" and "home energy monitoring" + "software" + "app". We used the general Google search, which revealed mostly businesses, and Google News, which led to several news sites' recommendation lists.

We sampled feedback displays that met the following criteria: (1) it was designed to or could be used to gain feedback on ones' home energy usage, (2) it had an interface (on a product or as software), and (3) it was designed for the residential consumer. The second criterion was important, as it excluded any home energy meters without its own data display (e.g. Aeon Labs Home Energy Meter) or other more basic products (e.g. Plug-In Power Meters or Amp Meter Analyzers) that are a part of the HEMS, but not the feedback solution.

Each product's website was visited, screen captures were collected, and data was manually coded in Excel. We took a grounded research perspective, evaluating the HEMS from three perspectives: (a) **what data** do they present; (b) **what visual** methods do they utilize; and (c) what **interaction** mechanics do they leverage. We established 83 variables (many beyond display descriptors) that were coded for each HEMS display. We grouped them into four categories:

1. *Corporate descriptors* (e.g., company, url, year, price, tagline, functions, etc.)
2. *Physical product* (item, shape, color, interface and its features, interactions, etc.)
3. *Software outside of the physical product* (e.g. platforms; interface; reporting, monitoring, and engagement features; status and history presentation, ratings, etc.)
4. *System features* (e.g. icons, metaphors, aesthetics, consistency, style, color, etc.)

Given the length-limitation of this paper, we shall limit our results and discussion sections to the most pertinent part of the HEMS feedback, namely what **data is presented** and **visualized** for feedback.

4 Results

We identified 75 currently on the market HEMS that have one or more feedback displays (N = 194) across multiple platforms. Most of the 62 products do not have a physical display, but are supported by feedback software on the web (N = 52) and/or mobile (60 iOS, 43 Android and 11 smart watch applications). Our sampled HEMS displays date from 2002 (Elgato's Eve) to 2016 (Sense), with 75 % (N = 55) launching in 2011 or later. Peak launch years were 2011 (N = 14) and 2014 (N = 16) (Fig. 1).

Fig. 1. Some sampled HEMS hardware (Blue Line Innovations, Wattvision, Curb, Smappee, Sense), thermostats (Energate, Lyric, Cosy) and feedback displays (Sentri, Energy Orb, Minim)

62 of the covered HEMS include **physical products**, costing between $25 and $300. Current homes require add-on products to smart meters (e.g. Blue Line Innovations) or fuse boxes (e.g. Neurio) to capture the energy consumption data. Some products include physical feedback displays (e.g. Sentri, Ambient Devices, Geo) and/or smart thermostats (e.g. Nest, Ecobee, Honeywell's Lyric), while others are a more technical set of gateways and Wi-Fi transmitters, with smart-plugs (e.g. WeMo, EnergyUFO, iDevices) or energy current sensors (e.g. Neurio, WattVision, Curb).

Data on in-home **feedback displays** is minimal and focused on the current consumption, occasionally production status. Contextualizing data in the different in-home feedback displays includes time, date, indoor and outdoor temperatures (F) and humidity levels (%), weather condition (icon), air quality (parts per million), current and next appliance status (e.g. on, off, idle, and schedule modes, such as auto, sleep, wake up, cozy or away), current hour's energy rate (kWh), if it is off- or on-peak, daily and monthly cumulative and estimated consumption volume (W, kWh) and costs ($), PV power generation (kWh, kW or W), if one is saving or not ($), and today's trend (in comparison to the day before, average, or other households). The physical become aesthetically pleasing, but still only a few have graphic interfaces.

Most **web** (N = 52) and **mobile** (N = 114) **applications** come free with HEMS products (e.g. Lyric, Sentri, SiteSage Energy Monitor), solar panels (e.g. SunEdison Echo, MySolarCity, OutBack Power's OpticsRe), or utility providers (e.g. Opower, Direct Energy, SimpleEnergy). Only a few function independently, compatible with the independent hardware (e.g. MiraWatt's T5K mobile app, Electricity Monitor by M. Tarmastin). The mobile applications function on iOS (N = 60) and Android (N = 43) platforms, with 11 smart watch apps (e.g. Honeywell's Ecobee, Nest and iDevices) (Fig. 2).

Fig. 2. Some sampled feedback software: Smappee (history), Nest (scheduling), Efargy Energy (dashboard), iDevices (pre-heating oven), Curb (live itemization), Direct Energy (monthly bill)

The **feedback software** builds on in-home displays in terms of information complexity, but each platform has its unique functions, varying their data accordingly. Data is most comprehensive on the web where current status, progress, history, estimation and other feedback information is presented for analysis and long-term decision-making. Mobile applications focus on the current status and afford users remote short-term controls beyond energy monitoring. Smart watches, available with some thermostats, connected devices and recently with energy monitors, relay only numeric statuses (e.g. levels, modes and active appliances) and alerts (e.g. fridge door open or kids arrived home), which are readily editable or actionable.

All feedback software are dashboards with small tiles or pages that communicate a specific data point. Common topics include current consumption summary (kWh, $, averages, comparisons, breakdown of biggest consumers), usage history over time (hourly, daily, weekly, monthly, and some even compare years), projections, bill estimation and whether the user is on target (with personal or social goals), real time energy demand that determines the hourly energy prices and affects items opted into demand response programs (approximate four price tiers are $0.04, $0.13, $0.25, and $0.47 for a kWh), appliance manager (i.e. scheduling and/or automating thermostats, lights, security cameras, washers, fridges, and other appliances), and personalized energy saving recommendations. Most data is presented numerically or in classic data charts. Varying visualizations are used for different data:

Representation of current status: Most display statuses are presented in raw units (e.g. KWh, $), though ambient use of colored light appears in about one third of the product displays. Feedback software focuses more on cost-savings, commonly presented as radial doughnut graphs around aggregated numeric values. Speedometer type gauge visualizations are also common for showing the Grid's status on the web. iDevices is the only watch app that uses a line graph to show a pre-heating oven.

Icons for good-bad status: Only a few displays use graphic icons to help relay the current status. Visual icons are commonly used for weather conditions, time, and good-bad status. A green leaf and tick mark are common signifiers of efficient hourly consumption rates. Red icons, strips or other alerting labels are used to warn users of pricey on-peak times (e.g. United Energy).

Color-coding information: Thermostats often use cool blues and warm oranges to signify cooling and heating process, respectively. Ambient lights from blue (off) and green (normal) to yellow (heads up) and red (warning) are used for current consumption levels, or to differentiate between the peak and off-peak rates. Same colors are also used on historical graphs to point out lowest and highest consumption points. Many solar apps prefer to use sun-related warm colors like orange and yellow.

Comparative status graphs: Only some displays have radial or gauge graphs to show the current consumption as a proportional value (e.g. Sentri, Geo's Soto III and Cisco's CGH-100 Tablet). Geo's Chorus II PV, the only in-home display for solar production, uses colored bars to compare users' production to their consumption, showing immediate money made or lost (solar sold or energy bought). A common benchmarking measure is the concept of '*always on,*' which refers to a house's baseline consumption. It is visualized as a dash on bar or radial consumption graphs.

Social status benchmarking: Users' cost-savings data is often mapped against their previously set goals, past consumption or other households. Comparisons against one's own budget or anonymous households tend to be visualized by a marker positioning the user in an ordinary stacked horizontal bar (e.g. efficient-inefficient scale).

Status itemization: Most current status itemizations are presented as active ranks of rooms, appliances or circuits (that mix rooms and appliances). Some visualize the lists with horizontal or vertical bars comparing their relative activity and/or costs. Rare solutions show circuits as actively moving meter reader dials on a circle or currently active appliances as an animated bubble chart, where bubble's sizes cue to their relative consumption volume.

Historical graphs: Consumption, production, temperature, humidity and other historic trend data are typically the largest graphs and presented as line, area, bar or histogram charts over some time unit (hours, days, weeks, and months). Thermostats often visualize energy data as bars, while temperature and air quality data as a line. Pixel visualizations over a calendar month have also been used. Sentri is the only physical feedback display large enough to show history data for temperature, air quality and humidity. It uses a filled area chart with simple time filters for different periods (day, week or a month). Nest's small thermostat does not display consumption, but weekly heating or cooling schedules as long hourly bars with bubble markers.

Historical comparisons: Newer apps integrate energy rates into usage graphs as stacked or differently colored bar charts. Others map past usage against user's average consumption, personally set goals, or past year. These lines are either emphasized in full accent color, or dashed and blending into the background. Solar compatible software visualizes consumption, production, energy sold back to the grid, and at times even '*always on*' data all in one stacked or clustered bar, line, area or bubble graphs. Predictions for the day, week or year continue as dashed line graphs or add-on filters that cluster or stack the bar charts for current-past comparison.

Monthly billing: Bills are monthly snapshot reports available via software. Monthly cost at the heart of a radial chart itemizing the bill is typical. Further details on each room, circuit or appliance can be accessed by filtering all else from view or deep diving into their 24 h usage clocks where each hour is colored with light to dark intensity, corresponding to little and much usage, respectively.

User controls: All mobile applications allow users some remote controls and scheduling options. Interfaces list currently active devices allowing users to control their lights (on-off, but also hues and density levels), door locks, sprinklers, security cameras, thermostats, to name a few, and even to pre-heat ovens (iDevices). Scheduling interfaces are either line or column based, and use the conventional blue-red or orange colors to color in active hours of the day. These come with unusual pattern alerts, safety warning and saving recommendations.

HEMS and control systems are separate services, but the emerging smart thermostats, –plugs and HMS are integrating into energy aware control of one's home.

5 Discussion

We used Nielsen's website heuristics [18] to help organize the strengths and limitations. We preferred Nielsen's heuristics over other information visualization specific heuristics, because the casual everyday user of HEMS is more familiar with websites than executing rational analytical tasks on interactive information visualizations. Due to space limitation, we shall focus on the *data* and *visualization methods*, while only briefly noting *interaction mechanics* as we discuss potential directions.

5.1 Strengths: Reporting Data

Reporting is the most basic function of feedback and knowledge management. In personal energy consumption context it refers to the verification of one's home consuming energy, the 'invisible' product. Monthly energy bills used to relay our house consumption data in a few numeric measures (kWh) that no one could relate to. Todays' HEMS capture an increasing volume of energy consumption data, decode and itemize it with little delay. As such, the primary benefit of current HEMS is their ability to deliver visibility and awareness to: (1) the continuous nature of energy consumption, (2) how it costs and (3) users' position against benchmarks. Main presentation strengths include (1) flexible to look back in time, (2) correlate data for quick insights, and (3) intuitive and consistent use of color codes.

Visibility of system usage: The currently dyadic product – software ecosystem divides the data reporting into current and historical descriptors, making it readily available. The continuous in-home reporting together with mobile alerts helps user's to experientially become aware of the continuous nature of energy consumption. As such, current

HEMS have addressed key issue with retrospective billing that has been observed to lead to cognitive disconnect between energy and its consumption [19].

Visibility of system cost: While the kWh unit remains cumbersome, the visually relative breakdown of bill items allows users to make sense what they are using, and what adds up to their cost.

Help users recognize errors: The numerous benchmark comparisons to ideal standards (e.g. budget), personal, or social variables (e.g. neighbors) afford an important personal value that supports the effectiveness of one's goal setting [10].

Help users diagnose errors: Different time frames into past data, complemented with visual comparisons to goals, average and the past, offer users insights into their progress and behavior. Itemizing past data into a list of appliances and visualizing their consumption, allows users to see what adds to the '*always on*' level.

Error prevention: Seeing how much energy is used when and by which rooms or appliances, combined with anomaly recognition, allows users to identify savings opportunities and understand how their house consumes energy. Correlating different data, such as energy usage and outdoor temperature (Bridgely), helps users visually capture their inter-relations. More literally, HEMS also alert users when consumption, budget or individual appliance values exceed pre-defined thresholds, helping them with budgeting, excessive usage, inefficient appliances and product failures.

Recognition rather than recall: Icons, like the popular green leaf are popular signals for when the user is doing. Animating the icons to cumulatively fill with or empty from color adds proportional information that is actionable (e.g. low prepay needs payment renewal). It is a common standard for thermostats to use cool blues and warm reds to intuitively help users grasp the cooling and heating modes, respectively. Similarly, green-yellow-red or light-dark saturation increments, is an easy to comprehend proxy for low-high energy consumption and costs.

In summary, current HEMS do well at increasing awareness and some basic comprehension of one's energy consumption and cost, but comprehension of the Smart Grid and energy as a public resource, remain unexplained.

5.2 Pitfalls: The Dull Monitoring

Monitoring refers to users' active engagement with real-time and/or historical data display and involves gaining insights. Given HEMS' intermediary role between utility providers and users, they hold the potential to engage users in energy Grid management. Problematically, current HEMS do not support information adoption beyond simple awareness. The dull data-centric presentations fail to entice users in active engagement [11]. Comprehension is hindered by: (1) lack of feedback at the point of consumption, (2) meaningless units (Watt, kWh and low energy prices), (3) inefficient data presentation, (4) dull visualization techniques, (5) inconsistent data presentation, and (6) lack of feedback customizability.

Visibility at point of consumption: Current HEMS feedback is readily available when users seek it, but most in-home displays are clunky tablets, stuck in one location, and affording little utility beyond current status. As a result, it is easy for users to ignore the devices [11]. In the emerging HMS context, more immediate feedback is needed to engage users with their homes' energy [10]. Energy Star's success relied on the point of consumption presentation [12].

Match between system and real world: Studies have confirmed users' struggles to comprehend kWh [20], yet few alternative units have been proposed (e.g. CO2 contribution, gas/mileage, light bulb hours) that could help users translate and comprehend the energy unit. Feedback should be presented in a format relevant to user needs and in an easy to comprehend way [10].

Lack of visual efficiency: Many interfaces have flawed layouts and lack information presentations. Current dashboards make it hard to correlate meaningful insights in ones' head, resulting in too heavy cognitive load for the casual home environment. In addition, the limited use of visual metaphors for numeric values and long incomprehensible lists are hindering understanding and users' interest in the data.

Aesthetics and minimalist design: The feedback interfaces have become more minimal over time; however, the data presentation has not. An alternative to long lists is a screen full of icons that leverages our visual capacity. Yet, only a few outliers use icons in place of numeric values that are significantly less engaging and graspable. Currently, users have to take many steps to open, launch and engage with the feedback data. Utilizing visual metaphors that users are familiar with from their daily life (e.g. calendar), can help interpret multidimensional data.

Lack of consistency: Presenting rooms and appliances in one itemization graph, causes legibility, comprehension and possibly misinterpretation challenges due to high unit variances (e.g. a living room may consume $7.8 a month, while hallway lights only consume <$0.01). Inconsistent graph orientations and colors, furthermore, break users' ability to track variables throughout the software (e.g. yellow and blue for solar and utility), adding to the cognitive load problem in gaining insights.

Lack of visual user freedom: In-home product mobility and screen customizability are rare among current HEMS displays. Yet, it remains an important user engagement and personalization features. Geo's Cosy thermostat is unique in its mobility and variety of materials (e.g. plastic, wood). Honeywell's VoiceControl thermostat and Sentri home display are starting to think about the added value that allowing users to choose vibrant pink backgrounds or upload personal photos can bring.

Overall, current HEMS have two major pitfalls that need addressing: (1) "*energy information is boring,*" worsened by inconsistency [21] and (2) current data presentations that do not help users comprehend what energy is, where it comes from and why one should care about it beyond personal cost-efficiency [1, 12].

5.3 Potentials: Engaging Integrated Interactions

The rapid blending of home control, automation and HEMS is giving rise to comprehensive energy aware home management systems (HMS) that go well beyond energy monitoring. Herein, interactions refer to users' manual or automated responses to behavior data feedback. Current display-centric data-heavy feedback is insufficient for the emerging integrated HMS, where comfort and automation drive interactions.

A user centered design perspective that would treat feedback data visualization as a possible platform for experiential engagement, could lead to promising enhancements in how users increase their awareness and comprehension of energy. Some ways include: (1) situational awareness, (2) redefining energy via familiar metaphors, (3) physical interactions, (4) inclusion of consumer choice, (5) redefining the Grid as community (that one has impact on), (6) preventative feedback, and (7) artifact aesthetics of documentation.

Situational visibility at point of consumption: HEMS feedback should ask less of the users and contextually deliver the message at the exact time of use. To achieve this, future products should be subtle feedback platforms that make energy consumption visible during consumption and so aesthetically pleasing that people would want to display, rather than hide them. For example, STATIC's disappearing-pattern for the bathroom lose their patterns when you shower too long in hot water [22].

Match between the system and the future real world: Exploring ways how visually describe the kWh unit, the unique appliance consumption patterns or to totally redefine the energy unit, could help users achieve better comprehension of energy. Some artistic approaches to energy feedback have explored the metaphor of plants and their well-being. Serenity conceptualizes energy efficiency as a plant that dries in excess heat and rots in too humid air [23].

Interactive user control: Nest's physical interaction control of the device has seen much praise. Future product designs should seek to think more physically rather than digitally, about user interactions. Infotropism, is a physical manifestation of Serenity's digital plant metaphor, that uses a living but robotic plant as an interactive in-home feedback display [24].

User control and freedom: Future HEMS should become the primary mediators between the utilities and the users, empowering the users to not only pay bills via their systems, but also allow them to become aware and active consumers of different utility service options.

Grid as community: A shared sense of purpose, values and principles found in sustainable communities have been proven to increase the peoples perceived life quality [4]. Future HEMS should seek to help users see the social collectiveness in the Smart Grid that we all share.

Preventative freedom (towards home well-being): Future energy feedback should move beyond individual price-centric statuses and contextualize users in the broader Grid demand and its ideal status, that is, a flat stable energy consumption that has no morning and evening consumption spikes.

Aesthetics of documentation: Home energy monitoring is not an analytical work task. Future HEMS should explore spatial, physical and more experiential information visualization techniques for historical analysis and documentation. Instead of the classic line, bar and histogram charts on the web or mobile, the historical output could manifest as a personal information mural or data art. Artists seeking to raise questions rather than offer answers, leverage different engagement mechanism from the traditional efficiency driven technology usability in HCI [25]. Well-designed user experience design driven products can be informative and joyful at once.

Given the trends towards home automation and multidirectional Smart Grid, the HEMS in future HMS need to become more contextualized and experience driven. After all, many agree that "*the "killer app" of HEM has yet to surface*" [16].

6 Conclusions and Future Work

Move to more sustainable patterns of energy consumption remains one of the great societal challenges. To see an 'energy turnaround' we need to reduce personal energy consumption and shift to sustainable energy aware living [19]. Governments and the energy industry agree on the importance of engaging the demand side to drive behavioral change towards balancing the grid. Energy monitoring and feedback systems (HEMS) are seen centrifugal to this process of rising awareness and comprehension.

Our review of current HEMS on the market revealed the potential of the new market, but also concluded that the current HEMS do not support the future vision for a multi-directional Smart Grid where empowered users can act as products and consumers [3]. While much of the needed data is already available, HEMS feedback needs to move beyond basic screen based data visualizations, and towards information as a contextual experience. Despite wealthy literature on sustainable behavior, design suggestions for future feedback experiences are limited.

We conclude that there is a lack of engaging user-centered feedback interfaces, and call for user experience centric explorations into information as a potential platform for experience design. Our research hopes to raise questions, more than it seeks to answer questions as we point to our need to solve fundamental societal problems.

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