Human-Centered Technology Design for Energy Efficiency and Conservation

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ABSTRACT

Human-centered design (HCD) is the practice of designing systems for human use. This paper describes the discipline of human factors engineering, which has traditionally been applied to energy intensive complex systems such as automobiles and aircraft, and will look ahead to applications in sustainable systems design. The focus of HCD has been ensuring efficient and effective human-system performance, through application of design principles such as understanding the user, providing feedback, and minimizing cognitive load. These principles also apply to the design of sustainable socio-technical systems, both through specific device user interfaces and broader developments such as transportation systems and urban design. HCD design principles need to be embedded within a social-systems engineering model that considers the overall *constraints* of physical and institutional processes, the *cultural* aspects of designs and interventions, various *comfort* and *convenience* factors at the level of individual users, and the *cognitive* impacts of designs – the 5C model. Application of HCD will involve a more holistic view of human-systems than is traditionally adopted by government and industry. HCD methods can be useful in disaggregating the energy intensive aspects of lifestyle and work, as well as applying design principles to address the 5 C's.

Introduction

When the term "human factors" is used in the context of engineering, it is generally considered as the application of knowledge and principles concerning human physiology and psychology to the design of specific hardware and software systems or components. In the arena of energy consumption research, "human factors" has not usually been defined in this way, but instead in a broader conception of the human dimensions of energy use. For example, Lutzenhiser (1993) identified seven domains of human factors in energy analysis: (1) variability of behavior and energy use, (2) public opinion and attitudes, (3) effects of information and financial incentives, (4) social aspects of pricing, (5) energy use as a social process, (6) micro-behavior in consumption environments, and (7) macro-social patterning of consumption. Of these areas, the focus on micro-behavior in consumption is the closest to the standard conception of human factors as being focused on human-technology system interactions.

It is generally believed within the human-dimensions research community that social and behavioral science findings and concepts are not routinely applied in design endeavors, for either the supply or demand sides of the energy system. According to Shove et al (1998), the most visible application of social science in energy technology studies is contributing to the development and evaluation of promotional campaigns and programs. Although this marketing aspect is an important element of overall system implementation, social and behavioral data and principles can be much more broadly applied to design across the energy supply and demand system.

The purpose of this paper is to broaden the definition of "human factors" in energy consumption research to encompass the more engineering-oriented approach typically used in system design. In doing so we will illustrate the potential applications of human factors to systems and technologies intended to enhance energy efficiency and conservation, such as smart grid/smart meters and programmable thermostats. The basis of this discussion is a general model of human-centered design for sustainable energy systems. By providing more specific examples of the applicability of human factors to the energy system, we hope to make the current discussion of nudges and wedges for behavior change more concrete in terms of an actual engineering implementation process (Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009; Thaler & Sunstein, 2009).

Background

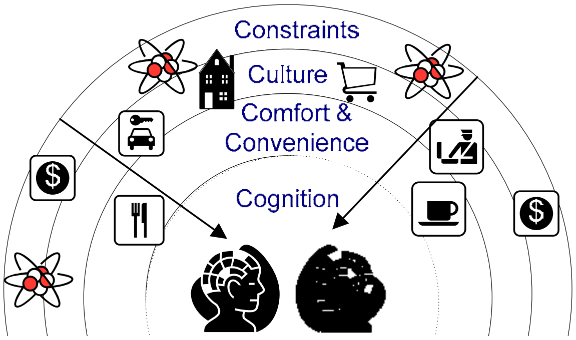
The relevance of human factors to both the supply and demand sides of the energy system is shown by analyses of system failure and success. The northeast blackout of 2003, for example, was associated with a loss of system operator "situational awareness" that was traced to a state estimator tool that was not placed back in service after maintenance (North American Electric Reliability Council, 2004); this illustrates human factors problems at both the individual cognitive (situational awareness) and organizational levels (deploying immature prototype software in an operational environment). On the demand side, several studies have now shown that programmable thermostats do not lead to the expected energy savings that would result from usage patterns based on engineering simulations; this is attributed to interface design problems and incompatibilities of the device with established patterns of use (Meier & Walker, 2007). Similarly, compact fluorescent light bulbs have encountered substantial resistance in the market due to various human factors-related performance problems, such as color, gradual increases in illumination following power-up, and negative attitudes toward fluorescent lights (Sandahl, Gilbride, Ledbetter, Steward, & Calwell, 2006). In contrast, a success story is provided by the recent application of behavioral principles to utility bill design, which is associated with small but persistent reductions in energy usage in residential settings (Allcott, 2010). Similarly, a considerable number of studies have shown that energy feedback via in-home devices or other means are associated with usage reductions (Ehrhardt-Martinez et al., 2010).

Human factors engineering has traditionally focused on the individual human-machine interface, due to the many safety problems induced by faulty designs that can be corrected at the device level. More recently, government agencies such as DOD and DOT have recognized that larger-scale "systems-of-systems" are introducing new and complex human factors issues that require a broader approach and perspective. In the energy domain, these issues are exemplified by the need for communication between planning, generating, transmission and consumption elements in a more dynamic fashion. As a tighter linkage is established between consumer and utilities, human factors design methods and data can be applied throughout the entire design, development and deployment lifecycle for products such as home energy management systems and feedback devices.

A Human-Centered Design Model of Energy Use

Human-technology interaction concepts from the energy research literature stress a model of social change that links multiple system levels (Rip & Kemp, 1998; Shove, 2003). Human-centered design addresses the influence of environmental, social, team and cognitive levels of analysis (Czaja, 1997). A synthesis of these two approaches is shown in Figure 1, which blends sociological and systems engineering concepts into a human-centered design model incorporating the complexity of the energy supply and demand system.

Figure 1. Human-Centered Design Model for Energy Usage



The key elements of this model include *constraints* in the physical, financial and political environment that influence what can or will be designed. Constraints can apply across multiple system levels – social, system, program and device. These constraints interact with the *culture* in which design takes place –which organization(s) specify design requirements, and the end user values and attitudes concerning technology and energy. *Comfort* and *convenience* are key perceptual features of energy consuming technologies and the services they provide; *cognition* refers to the individual mental processes associated with technology use, such as expected mode of operation, understanding of the underlying principles, and the inherent limits of human information processing capacity.

These model elements interact. Culture, for example, can create design constraints in terms of what people will or won't buy and use, based on existing mental models (cognition) of the comfort and convenience various technologies might represent. The utility of this 5-C model is that it can be used to represent human-centered design concerns across a range of influences on energy consumption. It can provide a basis for dialogue among the multiple stakeholders engaged in technology development, including government agencies, utilities, state regulators, technology developers, retailers and end users.

There is a range of human-centered design techniques to address issues across the development lifecycle, including participatory design methods in the early stages of managing stakeholder involvement (constraints, culture), more focused task analytic methods to develop specific designs (comfort, convenience, cognition), and numerous evaluation procedures to assess system performance. A variety of resources are available describing human-centered design approaches in more detail (Stanton, Hedge, Brookhuis, Salas, & Hendrick, 2005). The field of human-centered designs has evolved a number of general principles to guide product and system development, including the following:

- Know and understand the user base
- Ensure ergonomic and physical designs are correct
- Provide feedback
- Reduce mental workload
- Design for error tolerance or reduction

- Allocate function properly between humans and automation
- Form should follow function

These guiding principles for design are meant to address concerns that arise over the development life cycle; in the case of the energy system, this is a continuous process. Table 1 provides a detailed illustration of the 5-C model applied to specific energy consumer technologies, and selected application of human factors principles and methods. In the subsequent sections we further discuss these issues.

Table 1. The 5-C Model Applied to Specific Technologies with Selected Human Factors Principles That can be Applied to Address the Issues

5-C Model Element	Technology		Selected Human Factors Principle Application
	In-Home Energy Feedback Systems	Programmable Thermostats	
Constraints	• Physical limits in existing homes • Market Availability • Level of utility support	• Communication with grid • Integration of data from multiple utilities (gas, electric) and physical display limits • Location in older homes	• Define user base, consumer segments • Define system level goals (e.g., energy reduction) at device level
	Integration of design with utility service and national goals for energy reduction		
Culture	• Device proliferation • Techno-centric approach to energy reduction	• Diversity of end users • Level of user technology sophistication	• Embed functions in popular forms (e.g., phone apps, web/cable TV interfaces)
Convenience & Comfort	• Location in home • Impact on thermal comfort • Impact on daily routines	• Habits/routines • Ergonomics • Temperature preferences • Expected thermal comfort impacts of setback	• Definition of user scenarios – who, what, when? • Proper level of automation and user interaction • Proper ergonomic design
Cognition	• Ease of use • Persistence of use	• Understanding of programming method • Interaction of program limits with preferences	• Reduce mental workload in programming • Provide feedback on programming • Provide packaged selections to reduce error

Opportunities for Human-Centered Design in the Energy System

Since the emerging opportunities for human-centered design tend to revolve around exploiting the information processing capabilities of the "smart grid," some brief background on the policy goals of this system will help to establish the context. According to the Federal Energy Regulatory Commission (2009), the smart grid will:

> "apply digital technologies to the grid, and enable real-time coordination of information from generation supply resources, demand resources, and distributed energy resources (DER). This will bring new efficiencies to the electric system through improved communication and coordination between utilities and with the grid, which will translate into savings in the provision of electric service. Ultimately the smart grid will facilitate consumer transactions and allow consumers to better manage their electric energy costs." [emphasis added] (pp. 1-2)

This statement involves all 5 elements of the 5-C model, including constraints at the physical implementation level (generation and transmission resources), a cultural expectation of increasing digital control, comfort and convenience through reliability and cost savings, and cognitive enhancements through better information management. The policy statement identifies grid control and smart metering as key mechanisms, and discusses the need to "render data into a suitable form for human operators" (p. 27) as well as providing a variety of information and control services to consumers. It is more likely that these end-user goals will be achieved through the application of human-centered design throughout the development process.

In-Home Energy Feedback Systems

There has been a shift in research emphasis recently from traditional demand-side management (DSM) programs involving efficiency, to more technologically-based methods involving energy feedback devices and time-varying rate structures (Ehrhardt-Martinez et al., 2010; Faruqui, Sergici, & Sharif, in press). Referring to Table 1, the constraints in this general approach include the availability of in-home devices, the ability to provide detailed usage data in retrofit installations, and the general level of support provided by utilities for feedback devices. At the present time, utilities seem to prefer that consumers or other parties provide feedback devices, since this is not a core aspect of the typical utility business model (this is also a "business culture" issue). Cultural considerations involve the increasing "device proliferation" among consumers (International Energy Agency, 2009), and a general tendency to use more technology to address a technology-induced problem. Comfort and convenience issues with in-home feedback devices involve location in the home, the impact on daily routines, and the impact on various aspects of comfort. A feedback device will only be effective to the extent that consumers can easily interact with it, so centrality of location with respect to daily routines should be addressed in human-centered design. Cognition will be a key design parameter for in-home energy feedback and management systems, as research has shown different patterns in how people interact with these devices that will influence their long-term effectiveness; these include an initial *exploration* stage, followed by *awareness of energy usage*, followed by ad hoc *querying and diagnosing* (Fitzpatrick & Smith, 2009).

Developing effective in-home feedback devices involves issues related to information content and presentation, covering levels from the device to social and organizational. Numerous studies of in-home display systems (see example in Figure 2) have shown household energy savings related to both the presence of the device, as well as pricing and payment method

(Faruqui et al., in press). Pre-payment or pay-as-you go systems, for example, appear to generate reliable and persistent savings whether there is an in-home device or not. This finding reinforces the human-centered design principle of "direct feedback," i.e., providing feedback at the time of energy service use[1]. Considerable research indicates that direct feedback is a surrogate for positive reinforcement (such as energy savings).

Figure 2. Examples of in-Home Display Feedback and Control Devices

Achieving the goals of the smart grid will be somewhat dependent on how well consumers can be engaged to manage their energy consumption. While in-home feedback devices offer this potential, it is important that the devices and programs be designed and introduced to accommodate end-user expectations. Recent experience in large-scale smart meter introductions (without an in-home device) has shown consumer resistance due to disparities between energy usage measured by new and old meters (Wald, 2009) and lack of an obvious time-of-use price indicator (Smart Meters.com, 2009). In Table 2, we show the direct relationship between smart grid design goals (U.S. Department of Energy, 2009), and related human-centered design goals for in-home feedback devices. These design goals are associated with various challenges (constraints) derived from the 5-C model and human-centered design methods, data and analytic approaches to address the goals.

The design goals listed in Table 2 are important for achieving high rates of feedback device utilization and effectiveness. Similarly, the movement toward dynamic pricing will need to develop variable utility rates that are acceptable to consumers; if the variation is too high or low or the rate changes too quickly, desired savings will not be achieved. Usage-specific feedback and integrated energy management are related design goals that should be addressed within the overall process of hardware and software design. Engagement of utilities and third-party data providers in the design process can facilitate providing this type of information.

Achieving these goals is an iterative process of human-centered design that involves addressing the constraints and issues listed above. Specific approaches and methods are shown in Tables 1 and 2 that are applicable to these issues – the nature of the overall systems engineering process determines the extent of application throughout design, implementation and evaluation. At this point in time it is a fair question as to whether there *is* an overall systems engineering process, since the development of feedback devices seems to be pursued largely by device manufacturers and third-party providers without involving tight linkages to utilities (Ehrhardt-Martinez et al., 2010). As suggested by Honebein, Cammarano and Donnelly (2009),

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[1] Direct feedback is in contrast to indirect or "extrinsic" feedback, in which information about consumption is provided after energy is consumed – as is typical with a utility bill.

smart meters will either "ripen or rot on the walls of the world's homes and businesses" depending on the extent to which the human element is addressed continuously throughout the design process.

Table 2. Human-Centered Design Considerations and Approaches for In-Home Feedback Devices

Smart Grid Design Goals	Human-Centered Design Goals	Human-Centered Design Constraints and Issues from the 5-C Model	Human-Centered Design Principles, Methods, Data and Analytic Approaches
Informed participation by consumers	Direct feedback and positive reinforcement	• Data Sources for feedback • Location in home • Comparative usage	• Principle: Provide feedback • Task analysis of household-level behavior clusters • Space usage patterns and links
Correctly designed and operated markets	Acceptable utility rate structure	• Utility regulations • Changes in power portfolio • Unanticipated capital costs	• Principle: Know the user • Parametric field study with household activity logs • Post study debrief
New products and services	Device and usage-specific feedback	• Retrofit limitations • Units, time scales, graphics • Level of automation	• Principles: Proper function allocation; Reduce mental workload • Data display standards • User cognitive models of energy consumption
Optimized asset utilization	Integrated home energy management	• Interoperability across diverse appliances and displays • Integration with web-based services	• Principle: Form follows function • Operational concepts based on household technologies and activities

Residential Programmable Thermostats

Residential programmable thermostats control roughly 8% of the nation's energy use and are ubiquitous in single family homes. The electronic, programmable, thermostat has become the standard means of controlling heating, cooling, and ventilation in American homes. About 42% of American households had programmable thermostats in 2008, but nearly all new units being installed are programmable. Referring to Table 1, the constraints with this device include what can be displayed and controlled from a device formerly considered as a "switch." This involves, potentially, the need for communication with the grid, integration of multiple data streams, and appropriate location within the house. Cultural issues include a diversity of end users with varying levels of information technology sophistication. Comfort and convenience issues in this context tend to be related to ergonomics, habitual interactions, thermal preferences and expected impact of temperature changes on comfort. Cognitive aspects involve the degree to which end users understand the underlying programming and control model, and how that interacts with their preferences for temperature settings.

The typical programmable thermostat includes the ability to create a complex schedule with different temperatures for different parts of the day and days of the week. Various controls allow the occupant to enter information, temporarily override the schedule, or to set the temperature on long-term hold. Nearly all new units have digital displays, although their sizes, resolution, color, and amount of information displayed vary widely. The most elaborate thermostats are further connected to the internet ("communicating thermostats"). Simulations of building energy use have demonstrated that temperature set-backs (or set-ups for air conditioning) will reduce a home's energy consumption. The savings depend on the extent of set-backs, thermal characteristics of the home, and the climate. Based on these simulations, Energy Star and other efficiency programs have strongly recommended installation of programmable thermostats as a low-cost energy-conservation measure resulting in significant savings.

In the past 10 years, considerable evidence has accrued that programmable thermostats have not achieved the savings indicated by engineering simulations. Studies from a range of climates have found that homes with programmable thermostats consumed more energy than those homes equipped with older, manual thermostats. A summary of those studies is shown in Table 3.

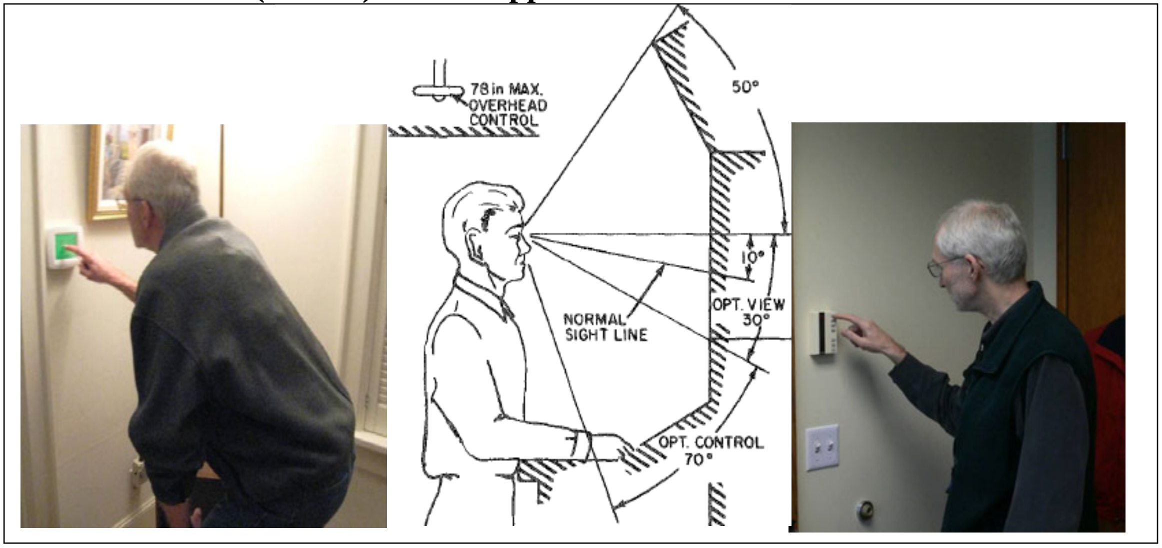
Table 3. Summary of Research Findings on Programmable Thermostats and Behavior Change

Organization	**Investigators**	**Region**	**Sample Size**	**Conclusions**
Energy Center of Wisconsin	Nevius & Pigg, (2000)	Wisconsin	299 homes	No significant savings
Connecticut Natural Gas	Cross & Judd, (1997)	Connecticut	100 homes	No significant change
BPA/PNNL	Conner, (2001)	Northwest	150 homes	No significant change
Florida Solar Energy Center	Parker, (2000) (unpublished study)	Florida	150 homes	No savings, some increases

This surprising conclusion can be partly explained by occupants already manually setting-back their thermostats at night or during periods of absence – a habitual element related to convenience and comfort. Also, none of the studies directly measured changes in energy consumption as households switched from manual thermostats to programmable units, so the two groups of households may differ. But other information collected in these studies and elsewhere suggested that **usability** was a major explanation for absence of energy savings from the programmable thermostats. For example, a significant fraction of the households kept the thermostats on long-term hold (thus negating the energy-saving benefits of temperature set-backs). Considerable anecdotal evidence suggested occupants often failed to enter the date and time (or failed to re-enter it after replacing the batteries). The absence of observable savings was sufficient evidence for Energy Star to terminate its endorsement program for programmable thermostats in 2009.

Modern programmable thermostats have numerous usability problems (and nearly everybody has a story about problems programming a thermostat). Terms and symbols are often obscure. Many words are drastically abbreviated—"tmp", "prg", "hld", etc.—to conserve space. One major manufacturer decided that it would use only words—in English—and avoid symbols and icons altogether. A red status light on one thermostat may be represented by a green light on another. Buttons and switches are small and closely packed. The font size of the labels is typically small. Partial instructions are sometimes affixed. Programming often requires complex key strokes, with awkward procedures for editing and correction. Thermostats are frequently located in rooms with poor light and at heights that are awkward for many occupants – see Figure 3. Few people will pull up a chair and study the thermostat (even though this is how a major consumer organization recently evaluated them!).

Figure 3. Thermostat Ergonomics Can Influence Effective Use. Human Factors Design Standards (Middle) Can be Applied to Prevent or Correct Problems



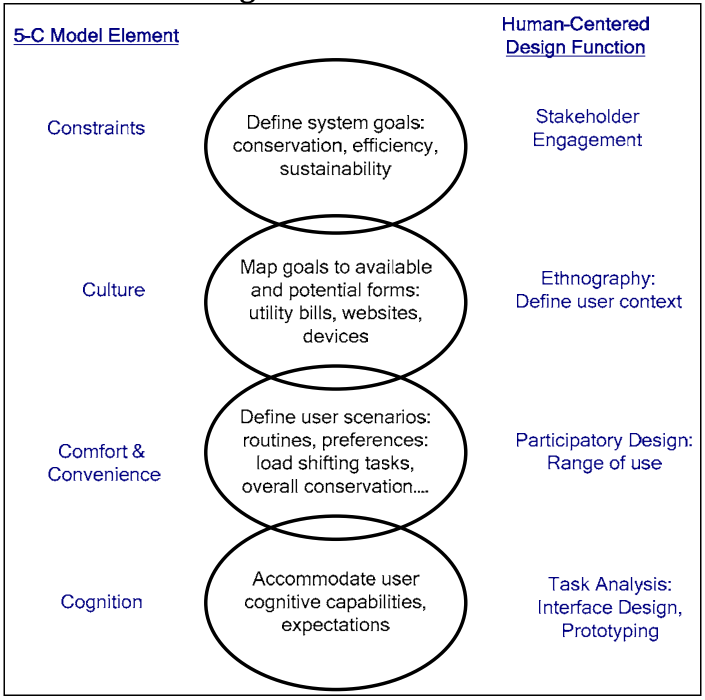
Looking to the future, how does one design a thermostat with a high degree of usability? The overall goal is to enable occupants to realize their thermal comfort preferences while ensuring efficient operation, but the usability goals may be much narrower. Usability criteria might be limited to performing the key tasks, such as ease of setting the time, establishing heating and cooling schedules, and setting (and removing) long-term temperature holds. The mapping between the overall system goals of comfort and the device goals of usability represents the key human-centered design challenge for programmable thermostats. In-home task analysis of cognitive models of thermostat usage would be a principal method in addressing this challenge.

Discussion

Human-centered design would appear to have a central role in facilitating greater involvement of end users in the energy supply and demand system to achieve increased efficiencies and less intense resource utilization. Numerous design issues that have been central in more traditional human factors domains also appear to be relevant in the energy system, including applying the appropriate degree of automation, balancing the information processing and display capabilities of new technology, and inserting new technologies into established routines of behavior. Meeting these challenges needs to take place across multiple levels of the socio-technical system to address specific physical and operational constraints, cultural expectations and practices, established patterns of comfort and convenience, and the expression of these factors in user interfaces at the individual cognitive level.

Figure 4 illustrates a process through which human dimensions research can be applied in engineering implementation and system development. This process incorporates elements of a systems engineering model recently proposed by the National Research Council (2007) for human-systems integration throughout the engineering life cycle. The National Research Council findings address the need for viewing human-centered design as a continuous, iterative process.

Figure 4. Human-Centered Design Process for Efficiency and Conservation Programs and Products



The steps illustrated in Figure 4 are shown as overlapping activities, in recognition of the fact that there are fuzzy boundaries between the process elements, and that feedback from one stage to another is necessary. The initial process is definition of system goals for efficiency or conservation at the level of the most influential stakeholders, e.g., government, utilities, fuel suppliers, etc. This element of the process defines the overall set of constraints, including business practices, that influence design. Discussions of the smart grid, for example, are often framed in terms of “transforming a customer’s relationship with electricity.” Engagement of human-centered design concerns at this level of system conceptualization can help to provide operational specificity to such goals, which will then influence subsequent stages of the design and implementation process. This is probably the most challenging phase of design, since decisions made at this early point can constrain all further work. In the case of the energy system, definition of goals will require a high level of interaction among government, utilities, energy services companies, consumer product manufacturers and (potentially) consumer advocacy or watchdog organizations.

The cultural element of the design process involves mapping system-level goals into available and potential design forms. This is principally a conceptual exercise to determine all of the potential means available to deliver the design goals. Conservation and efficiency goals may be communicated or reinforced by numerous information channels available to the consumer, including discrete display devices, cable TV, websites, phone applications, text messaging, etc., as well as more traditional means such as utility bill-stuffers and outreach programs. Ethnographic studies of consumers can be very useful in determining the viability of various design forms that have established cultural associations.

Comfort and convenience elements are addressed through more detailed definition of user scenarios, such as household routines that may influence load shifting or reduction. Potential questions to address would be areas such as the “spare capacity” for load reduction in higher-consuming homes, or the flexibility to shift certain tasks to non-peak hours such as washing clothes or dishes. The main human-centered design function in this aspect of the process is to engage a range of potential consumers to define plausible scenarios of use, the range of activities to which conservation/efficiency measures can be applied, and how they would be applied. Participatory design methods such as focus groups and more structured exercises involving user modification of rough prototypes can be employed at this stage.

The cognitive element of design is addressed through a process of mapping what is known about human cognition to the specific end product. Feedback devices, for example, would be designed with user interaction techniques to facilitate information transfer and programming. Human engineering design standards are available to facilitate this process, and the core method is user task analysis, which defines information inputs, processing, and outputs that directly interface with the consumer.

Conclusions

A human-centered design process for systematically addressing the multiple interacting elements of conservation and efficiency is outlined. We have illustrated human factors issues and applications in the context of in-home energy feedback devices and programmable thermostat controls. The applicability of human-centered design approaches within these well-defined problem areas suggests that similar approaches might be taken to larger-scale human-service problems, such as transportation systems and urban design. It is these larger-scale areas where transformative change in energy consumption can yield the largest gains.

Implementation of a consumer-focused design process that engages all of the diverse stakeholders is not an easy undertaking. It is further complicated by fundamental issues related to traditional energy system business models, and ultimately the role of government in establishing and promoting efficiency and conservation goals. However, the history of human factors engineering was driven largely by the need to achieve specific efficiency goals in the work force, so there is a precedent for a “top-down” approach. To the extent that a similar process is applied to energy efficiency and conservation, human-centered design can provides a wide range of methods and concepts to address these complex issues.

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