Beyond Energy Monitors: Interaction, Energy, and Emerging Energy Systems

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ABSTRACT
Motivated by a recent surge of research related to energy and sustainability, this paper presents a review of energy-related work within HCI as well as from literature outside of HCI. Our review of energy-related HCI research identifies a central cluster of work focused on electricity consumption feedback (ECF). Our review of literature outside of HCI highlights a number of emerging energy systems trends of strong relevance to HCI and interaction design, including smart grid, demand response, and distributed generation technologies. We conclude by outlining a range of opportunities for HCI to engage with the experiential, behavioral, social, and cultural aspects of these emerging systems, including highlighting new areas for ECF research that move beyond our field's current focus on energy feedback displays to increase awareness and motivate individual conservation behavior.

Author Keywords
Energy; Electricity; Sustainability; Design

ACM Classification Keywords
H.5.m [Information Interfaces and presentation (e.g., HCI)]: Miscellaneous;

General Terms
Theory

INTRODUCTION
Energy has become established as an important topic of concern for HCI, particularly with respect to the area of sustainable HCI [e.g.,6,15]. Given the proliferation of research within HCI related to energy, now is a good time to review and assess current work within our field, as well as trends in literature from outside of HCI. Our review of energy-related work within HCI highlights a range of innovative contributions related to the design of energy feedback systems that aim to motivate sustainable consumption. However our review also reveals that current work is narrowly focused on a specific set of goals and interventions, namely increasing users' cognitive awareness of electricity consumption and promoting electricity conservation behavior by means of consumption feedback, particularly by visualizing energy consumption data. Our review of literature outside of HCI highlights a number of key areas of emerging energy systems that have not—with some notable exceptions [e.g.,48,55,61,70]—been significantly engaged with, including smart grid technologies, demand response appliances and infrastructure, real-time energy pricing, and small to large scale distributed and renewable generation such as wind and solar power.

Our primary goal and contribution in this paper is to help expand the types of energy-related work within HCI, both with respect to energy feedback systems and beyond. We give special attention to emerging energy systems, and outline and concretely illustrate that these types of systems offer a rich space for innovative and important HCI contributions. In line with others [e.g.,13,48,56,61,62], we draw attention to the emergence of new energy infrastructure, policy and areas of consumer applications as key opportunities for designers and researchers to intervene in order to redesign and reconfigure sustainable everyday technologies, practices, lifestyles and behaviors. Similar to the ways in which the introduction of electricity and accompanying technologies transformed everyday life and gave rise to new ways of living, the emergence of new energy systems are poised to have potentially radical effects on how energy is used and experienced in domestic, workplace and public contexts. At the same time, however, the opportunities for radical change afforded by shifts in energy regimes should be tempered with caution and concern for the potentially far-reaching negative consequences that may be introduced unintentionally by design [e.g.,9,57].

In what follows, we first give a review of energy-related HCI research and identify a dominant cluster of this work focused on electricity consumption feedback (ECF). While this paper is not specifically aimed at critiquing this cluster of work, we note that prior work within and outside of HCI has raised a number of criticisms of the types of approaches we have characterized as ECF. For example, Elizabeth Shove has argued that approaches to sustainable consumption aimed at changing individuals' behaviors and attitudes often have difficulty dealing with the dynamics of social change and the ways behavior is constrained by forces outside an individual's control [57]. Related criticisms can be found in the work of Dourish [17], DiSalvo et al. [15], Strengers [61] and others [e.g., 3,47].

Following our discussion of ECF research within HCI, we outline several critical yet largely overlooked areas of emerging energy systems for HCI. Surprisingly, given our field's concern with the topic of energy consumption and more generally with emerging technologies, many of these areas have yet to be explicitly highlighted and significantly engaged with within the HCI literature (and yet are pervasive across the more general body of literature dealing with energy systems research, development, policy, legislation, and design). Next we highlight several interactive projects that variously engage with aspects of the emerging energy systems presented. Some of this work is drawn from the authors' prior and ongoing research.

We conclude by outlining a range of opportunities and challenges for HCI and interaction design research related to energy and sustainability. These include both ways of expanding ECF research, as well as ways that HCI can expand beyond the goal of promoting sustainable behavior change by means of electricity consumption feedback.

ENERGY-RELATED RESEARCH WITHIN HCI

In this section we characterize and give an overview of current HCI research related to energy. This is based on our review of 51 papers related to "energy" [1] from HCI-oriented venues including the ACM CHI, OZCHI, UbiComp, DIS, TEI, NordiCHI, Persuasive and Pervasive conferences. Specifically we identified 2 journal articles, 32 papers published in conference proceedings, and 17 papers in extended abstracts. We did not review workshop papers or other non-peer reviewed papers.

Our review reveals a central cluster of research that we refer to as *electricity consumption feedback research* (ECF). This area represents roughly 70% of the HCI literature we reviewed dealing with electricity consumption, and 100% of the subset of this work that is both self-identified as related to "sustainability" and primarily contributes a novel design artifact. ECF is characterized by the following themes:

1. **Consumption feedback.** ECF research is focused on a specific type of intervention, namely presenting users with feedback based on electricity consumption data (e.g., the amount of electricity a home is consuming), typically displayed to users via a computational visualization.
2. **Energy awareness and conservation behavior**. ECF research is focused on a specific goal, namely promoting individual energy conservation behavior and/or cognitive awareness of energy consumption.

With only a few notable exceptions that contextualize their work within recent energy trends such as smart metering [e.g.,7,39,53,55], ECF can further be characterized by a third theme:

3. **Lack of engagement with emerging energy systems.** ECF research is mostly framed within current paradigms of energy production/consumption, namely centralized systems of production with limited capacity for integration with smart metering infrastructure, demand response, or distributed and renewable generation (areas which we review later in this paper).

Our review reveals three clusters of energy feedback research: (1) ECF displays and interfaces, (2) ECF technical infrastructure, and (3) qualitative studies informing ECF research and design. We give an overview of each in turn.

ECF displays and interfaces

The majority of the papers we reviewed focus on the design, implementation and/or evaluation of technologies that involve "feeding back" electricity consumption data to users via a computational display (27 papers total, roughly half of the literature we reviewed). 23 of these papers present a design artifact [e.g.,5,20,28,31,33,35,43,71]); 3 focus on outlining design recommendations or strategies for energy feedback design [21,27,45]; the remaining paper is a review of eco-feedback, which does not exclusively focus on electricity but does identify electricity consumption as the predominant focus of eco-feedback technology within HCI [22]. The majority of the papers focus on a specific context of electricity consumption, namely the domestic environment. Exceptions include a paper that focus on workplace consumption behavior [33] and a tool that provides feedback to software engineers [2]. We further note that all of the papers we reviewed were focused on electricity consumption in industrialized or "developed" contexts, typically upper-middle class populations (an issue also highlighted by Dillahunt et al. [14]).

Most papers employ a screen-based computational visualization [e.g.,7,31,35,43]. Others employ ambient displays utilizing lighting other than pixel-based displays [e.g.,23,28,33]). Most of these papers focus on energy consumption for the entire home or broken down for specific appliances. Only a few target interactions with a specific appliance or device via a display integrated with that appliance or device. These include feedback integrated with an electrical power cord [23], mobile screen-based devices [26], individual home power outlets [28,59], and home computers [35]. Most focus on providing feedback in order to inform or motivate conscious decision-making. A

[1] This group of 51 papers does not include papers we reviewed that focused on energy resources other the electrical energy. Interestingly, though perhaps not surprisingly, we found relatively few papers that focused on non-electrical energy. Two of these dealt with transportation and two with carbon-tracking more generally. We also found four papers that dealt with water consumption, each of which focused on feedback similar to that which characterizes ECF. Although these papers are relevant to our concern with energy and emerging energy systems, we chose to exclude them for simplicity and given they were relatively few in number.

few focus on unconsciously processed information, including subliminal information [24] and "unconscious", affordance-based persuasion [59]. One of the papers we reviewed is a persuasive game that did not directly measure energy consumption but rather simulated it in order to educate users about efficient consumption behaviors [5].

While we characterize this cluster as focused on the goals of increasing user awareness and/or motivating conservation behavior change via energy feedback, it is important to clarify that many of these papers additionally address some broader goals and concerns, such as curiosity and engagement [7], aesthetic experience [31], and playful competition [58]

ECF technical infrastructure

We identified a much smaller set of HCI-related papers that focus more on the technical challenges of sensing and feedback infrastructure for feedback interfaces, rather than the design of feedback interfaces themselves [42,51,54]. We also note that outside of HCI venues but within the computing literature more broadly (e.g., ACM conferences such as E-Energy and Build-Sys, and journals such as IEEE Pervasive Computing), a great deal of attention has been given to the technical challenges and opportunities presented by emerging energy technologies, such as the smart grid concept we discuss in the next section [e.g., 50,52].

Qualitative studies informing ECF research and design

We identified a number of papers that focus on user studies or other qualitative studies of electricity feedback systems and energy consumption practices [e.g.,10,11,14,53,55]. We characterized these studies as ECF research because they focus on design recommendations for energy feedback systems that encourage energy awareness and conservation behavior. However it should be noted that these papers also discuss some broader concerns such as power imbalances between landlords and tenants [14], limitations of financial incentives [10], and privacy issues related to personal energy consumption information [55].

Non-ECF research

We identified 4 clusters of research related to energy and HCI that we did not characterize as ECF. These were: (1) critical perspectives on energy feedback [46,47,60,61], (2) qualitative studies of energy consumption (without a predominant focus on ECF design recommendations) [8,40,70], (3) energy harvesting and human-powered interaction techniques [e.g.,4,41,66,67], and (4) design-theoretic treatments of energy [3,48,49]. (Here we reference two noteworthy papers [3,41] that deal with interactive technologies but which fall outside of the mainstream HCI venues we reviewed.) Collectively these papers deal with a range of emerging energy technologies, such as smart metering and small-scale power generation technologies. Later in this paper we highlight some of these projects in more detail. Next we discuss emerging energy systems.

EMERGING ENERGY SYSTEMS

We are currently witnessing a surge of technical and social innovation in the energy sector across various areas of academic research, government, and industry. However our review reveals that the HCI community has been slow to fully and explicitly engage with important areas of this work—either to build upon it or critique it. In this section we draw out and summarize several key areas for HCI research and design based on our review of literature related to emerging energy systems. In doing so, we highlight important opportunities for HCI and interaction design to play a role in proposing, exploring and shaping (or un-shaping) new interactive applications based on emerging technologies. We outline four commonly discussed areas of emerging energy systems (with a focus on technical infrastructure rather than social, cultural, economic, and political factors) that have strong relevance for HCI and interaction design. We conclude this section with a brief discussion of some criticisms of emerging energy systems.

Smart grid

Since the introduction of modern electricity generation in the late 1800's, modern electrical power grids have undergone remarkable evolution. Despite Thomas Edison's original vision of a largely distributed generation system [32], the modern power grids in most developed countries are centralized systems comprised primarily of large central-station generation connected by a high voltage network of grid to local electric distribution systems that serve homes, businesses and industry [18]. While this system has served industrial countries well in many regards, a host of concerns have arisen with this system, including climate change, energy security, the need to keep up with aging infrastructure, and risk of nuclear disaster (a concern rekindled by the recent Fukushima Dai-ichi nuclear disaster) [e.g.,30,64].

In response to these concerns, a "smart" electrical power grid, or *smart grid*, is being advocated, developed and in some cases implemented in countries around the world including Europe, the U.S., Australia, and China. While various definitions and visions of the smart grid exist across academic literature and publications from government and industry [30], the central aspect shared by these notions is the use of information technology applied to the electric power system [50]; "At a basic level, the smart grid will serve as the information technology backbone that enables widespread penetration of new technologies that today's electrical grid cannot support." [30, p. 30]. Other sources envision that smart grids of the future will be characterized by a shift "from a centralized, producer-controlled network to one that is less centralized and *more consumer-interactive* [emphasis added]." [64, p. 10].

Advanced metering infrastructure and smart meters

The concept of *advanced metering infrastructure (AMI)* is central to various definitions of the smart grid [30]. AMI refers to a network that allows for two-way communication between an electricity provider and the customer meter [30]. *Smart meters*, built on top of AMI, are utility meters that record real-time electricity consumption and report this data back to utility providers. Smart meters have been installed or are planned to be installed in countries including Italy, Japan, Canada, the U.K., the U.S., and Australia (see, e.g., [60,61,64,68]). In-home displays (IHDs) that report real-time energy consumption data enabled by smart meters are frequently discussed in the smart grid literature [e.g.,30], and have been implemented and studied [e.g.,60,61,70]. Smart meters and IHDs clearly dovetail with the types of home energy monitoring displays characteristic of current ECF research. However, AMI and smart meters are also significant in that they enable time-based electricity rates and demand response programs, which we discuss in the following section.

Demand response

ECF systems within HCI typically focus on motivating conservation behaviors such as turning off lights when not in use. However there is another major approach to improving the overall efficiency of the power grid called demand response. *Demand response (DR)* refers to a variety of programs and actions that involve customer/user response to particular conditions within the electricity system, such as peak period network congestion or high prices [63]. Demand response programs aim to transfer customer loads during periods of high-demand to off-peak periods, a strategy referred to as *load shifting* [12]. Load shifting can improve the overall efficiency of the power grid by flattening load curves and allowing more electricity to be provided by less expensive base load generation [12]. Demand response can also reduce the need for building additional generation capacity [12, 25].

Demand response and load shifting are particularly interesting areas to explore for HCI and interaction design because they can involve behavior and lifestyle changes that may be quite different from those falling in the category of energy conservation.

Distributed generation and renewable energy resources

The centralized power grids of most industrialized countries rely on large central generation facilities, typically fossil fuel or nuclear plants [18], which are tied to a range of concerns including global warming, threat of terrorist attack, and nuclear disaster. In response to these issues associated with centralized power systems a new trend toward developing distributed energy generation is emerging [e.g.,1,68,72]. While there is no clear consensus on the term *distributed generation (DG)* or related terms such as decentralized generation or on-site generation, DG is typically characterized by energy conversion units with smaller generation capacities (~3-10,000 kW) and which are situated physically closer to energy consumers [1,72]. In the most extreme case of distributed generation, buildings are completely self-supported with respect to generation of their electricity, heat and cooling energy [1]. Some common distributed generation systems include combined heat and power (CHP), fuel cells, microturbines, biomass, photovoltaic systems, and small-scale wind power systems. Generation using such sources to meet ones own energy needs is often referred to as *microgeneration*, and localized groupings of electricity generation and storage is typically referred to as a *microgrid*, or a *grid-tied electrical system* when it is linked to a centralized system (see, e.g., [68,72]).

While distributed and renewable generation has been advocated as means of addressing the inefficiencies with and environmental degrading nature of current centralized power systems, a number of challenges are presented by decentralized power systems, including high costs to produce, implement, and maintain them [e.g.,72]. A major issue discussed in the literature is the intermittent and distributed nature of distributed generation that is determined by local environmental conditions such as wind speeds and cloud cover, which can vary significantly even over short periods of hours or minutes [52]. This is often framed as an engineering problem in which strategies such as demand-response will have to be utilized to ensure electricity demand is matched to the available supply [52, 64]. Others have argued that the "problematic" intermittent and local character of distributed generation actually offer new opportunities for social empowerment [65], energy systems that are more compatible with "social diversity and freedom of choice" [38, p. 54], energy awareness and citizen participation in energy issues [13], more active consumer engagement through the co-provision of microgeneration services [68], and positive experiential engagement with one's local environment and community [48,62].

DG and its potentials for both integration with and independence from centralized power systems and the smart grid suggest a broad range of opportunities and challenges for HCI and interaction design. These range from new financial and non-financial incentives to conserve energy (e.g., by designing to amplifying feelings of ownership and responsibility over locally produced energy) to the design of new community sharing norms and practices.

Criticism of emerging energy systems

While proponents of a "smart grid" and related technical innovations argue these technologies can help solve pressing societal problems such as climate change and energy security, others have raised substantial criticisms of these technologies. One area of criticism highlights technical and economic issues. For example, some critics have questioned the cost-effectiveness of installing smart meters. Another area of criticism more deeply challenges the way emerging energy technologies are being positioned socially and politically. For example, Nobel Laureate John Byrne and colleagues argue that proponents of renewable generation hope to achieve technological revolution without addressing the social issue of "energy obesity" [9]. Such

Figure 1. Energy Memento (left) and Power-Aware Cord (right, image courtesy of Interactive Institute).

Figure 2. Bionic Energy Harvestor (left, image courtesy of Max Donelan) and Peppermill (right, image courtesy of Nicolas Villar and Steve Hodges).

criticisms are echoed in recent critiques within HCI [e.g.,6,15,17,48,61]. While this paper focuses on highlighting the opportunities presented by emerging energy systems, these types of criticisms should be taken into account. Indeed, they can be productively drawn on and developed by designers and researchers of interactive technologies in order to propose new ways of positioning and shaping emerging energy systems.

DESIGN CASES: INTERACTION FOR EMERGING ENERGY SYSTEMS

In this section we highlight several projects and areas of research involving interactive designs that variously deal with aspects of the emerging energy systems outlined previously. Some of these examples fall within mainstream HCI research while others originate from outside of HCI. We present these examples in order to concretely illustrate interaction-oriented energy research at the periphery of ECF research. Each project departs in some noteworthy way from either the goal of energy conservation/awareness or the design of a display for monitoring and displaying consumption data, or both. We organize these projects into three scales of focus: energy as a material, energy devices, and energy homes/communities.

Energy as a material

Static! and the aesthetics of energy

The Static! research group at the Interactive Institute was focused on a novel approach to interactive design research around energy. Two ideas were central to the group's research: exploring the aesthetics of energy as a design material and promoting critical reflection with respect to the use of energy [3]. The group prototyped an impressive range of artifacts related to these themes. One of the most commonly referenced artifacts is the Power Aware Cord, an electrical cord that visualizes the amount of electricity flowing through it using pulsing LED lighting (Figure 1). Several projects also made use of energy from small-scale renewable sources, including the Energy Tap—a public hand-crank electricity generator (Figure 3). While the presentation of several of these projects such as the Power Aware Cord fit within our characterization of ECF [23], the broader design theoretic approach presented by the Static! group [3] is unique in the way it moves beyond concerns with behavior change by conceptualizing ways that designers can craft electrical energy as a material in aesthetic and provocative ways.

Energy Mementos and energy metadata

Building on the work of the Static! group, authors Pierce and Paulos have designed a series of "Energy Mementos" with a goal of exploring energy as material that is experienced as a unique and meaningful thing [48]. A central theme this project investigates is the extent to which people can interpret and treat some energy differently than other energy. For example, the Shake-light bottle (Figure 1) allows someone to generate energy by shaking the bottle. The energy is then stored and may be given as a gift. Opening the bottle activates the energy as a stream of lights that directly correspond to the unique magnitudes of power generated by the individual that created the energy. Energy Mementos build on the concept of *energy metadata* that captures attributes of electrical energy [48]. These may include more commonly discussed attributes such as cost or technical characteristics such as voltage or frequency. However the metadata concept emphasizes a much broader range of less conventional attributes of electricity, such as how it was produced (e.g., wind, solar, coal), where it was produced, who produced it, and how far it has traveled.

Energy devices and interactions

Energy harvesting

Energy harvesting (or energy scavenging) is an area of research concerned with capturing and utilizing energy from human activities and other external sources such as ambient heat, often for mobile and wireless applications. A well-known example within the energy scavenging literature is Schenck and Paradiso's shoe-mounted piezoelectronic device (discussed in [41]). A more recent example is the knee-mounted biomechanical energy harvester that captures energy from walking [16] (Figure 2). Other types of energy scavenging devices capture ambient environmental energy from thermal, light and vibrational sources [41].

Human-powered electrical and electronic applications

While energy harvesting applications typically focus on extracting *passively* generated energy from humans or ambient environmental sources, other applications are designed for more *active* human-power generation. Current consumer applications of this variety include hand-powered flashlights, radios, and mobile phone chargers. A recent research exemplar is Villar and Hodges' Peppermill, a device that can power web-applications with human energy

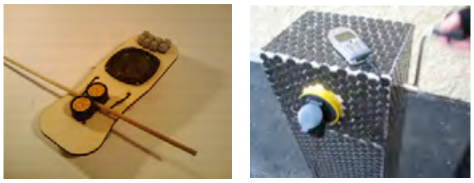

Figure 3. An Exertion Instrument (left, image courtesy of Noah Vawter) and Energy Tap (right, image courtesy of Interactive Institute).

[67] (Figure 2). Another noteworthy example is InGen, a self-powered wireless rotary input device that can generate haptic feedback without external power requirements [4]. Human-power generation and energy harvesting both offer a range of possibilities for new types of interactive applications.

Exertion Instruments

Designed and built by Noah Vawter at the MIT Media Lab, Exertion Instruments are hand-powered musical instruments that use electric or electronic oscillators for sound generation [66]. Exertion instruments are similar to traditional acoustic instruments in that the acoustic energy generated is directly proportional to the player's kinetic energy exerted into the instrument. Vawter has built a range of such instruments using a number of different types of interactive methods of electricity generation (e.g., Figure 3). Exertion instruments exemplify a novel application of human-powered electricity generation in order to explore new ways of engaging with and through electricity.

Energy homes and communities

The GridWise testbed demonstration

The Pacific Northwest GridWise Testbed demonstration was a field demonstration of smart grid technologies and programs that took place from 2006-2007 in the Pacific Northwest region of the U.S [25]. The project was funded by the U.S. Department of Energy and local utility companies. The GridWise project implemented and tested a wide range of smart grid technologies across approximately 100 homes, including the use of two-way communication between the power grid and microturbine distributed generation resources, real-time utility pricing for residential customers, and residential demand response for electric water heating, space heating and clothes dryers. Residents were able to set the "price responsiveness" based on a "comfort setting" for thermostats and water heaters, and clothes dryers were modified to display current pricing conditions. Residents were also able to view detailed historic and aggregated energy information for their homes from a website. Overall the project reports to have demonstrated peak load reduction based on demand response management and real-time price contracts.

Demand response and renewable energy displays

Within and outside of HCI, there have also been a number of qualitative studies of emerging energy technologies that are currently being manufactured, installed, and adopted in homes, such as domestic microgeneration and demand response displays. Woodruff et al. [70] have studied how

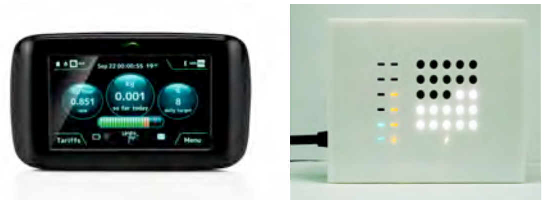

Figure 4. Landis+Gyr ecoMeter (left, image courtesy of Landis+Gyr) and The Local Energy Indicator (right).

eco-conscious consumers adopt and use new energy technologies. Strengers [61] has investigated how Australian eco-communities use the commercially available ecoMeter, which is unique from many other home energy monitors in that it displays periods of high, medium and low energy demand. Authors Pierce and Paulos have explored other ways of displaying information about the source of electricity [48], such as a lamp that communicates the source of energy by changing its color, and a home display showing the amount of available wind and solar energy (Figure 4).

RESEARCH AND DESIGN OPPORTUNITIES

Based on the areas of emerging energy systems and specific projects we have highlighted, we outline a number of opportunity areas for energy-related HCI research. Our goal is to demonstrate and advocate a broadening of research concerns, approaches, and projects within HCI and interaction design.

Designing new data, products, services and systems (Beyond monitoring home energy consumption)

We have characterized current energy-related HCI research as focused on a particular type of technology: energy feedback displays for consumption data. Here we outline a broader range of data, products, environments, services, and systems that ECF and other areas of HCI can engage with, particularly in the context of emerging energy systems.

Displaying new data

Emerging energy systems suggest sets of data (or energy metadata [48]) that can be visualized and displayed in addition to the amount of energy consumed by a person or household. In the context of distributed and renewable generation, energy displays could also visualize the source of energy for homes connected to microgrids and distributed resources (e.g., Figure 4). Another emerging area is the display of dynamic energy pricing information. More generally, the emergence of demand response systems opens up a space for communicating not only energy consumption but also energy *demand*, such as informing dwellers of critical peak periods.

Redesigning everyday product interfaces and interactions

Prior work has tended to focus on displays that report aggregated or disaggregated consumption data for an entire household or building. However, there are also many unexplored opportunities to redesign everyday appliances and devices, ranging from mobile phone chargers to dishwashers to thermostats. One important emerging application area is demand response appliances. An example of DR appliance development is the GridWise study that utilized demand response electric clothes dryers, hot water heaters and thermostats. Projects such as the PowerAware Cord [23] (Figure 1) further suggest ways that different types of energy can be reflected in the interface of a product, possibly based on new types of energy metadata [48].

Bodily energy interaction (without visualization)

We have also reviewed projects that explore new product-level energy interactions that focus on bodily, tactile engagement more than visual or cognitive engagement. These include human-powered and other energy harvesting applications such as the shoe-mounted energy harvester, the Peppermill, and InGen [4,41,67]. There are also opportunities to build on these types of technologies to design new forms of experiential and social engagement, as demonstrated by projects like Exertion Instruments and the Energy Tap. These types of applications highlight the potential for designing new ways of engaging with, experiencing, and understanding energy based on a more direct, visible, and physical connection to the production of energy.

Designing for other types and contexts of energy

The vast majority of the projects we reviewed and highlighted focus on the consumption of electricity in domestic contexts. Only a few papers engaged with other contexts such as the workplace [e.g.,2,33,55]. With a few exceptions [e.g.,3,31], none focused on design for public or communal spaces such as cafes, parks, schools or museums. (However, outside of academic research artists and designers have engaged with such contexts; see, e.g., [45].) Our review also did not reveal any papers that focused on "developing contexts", such as intermittent electricity supply in areas of India. Finally, the overwhelming focus of the works we reviewed was electrical energy, rather than other energy resources like natural gas—a point that has been noted previously by Froelich et al. [22]. While there are good reasons to focus on electricity, the home, and developed contexts, there are also opportunities to expand beyond these focuses.

Using energy differently (beyond "using less")

We have argued that energy-related HCI research is currently narrowly focused on the goal of promoting conservation behavior, i.e., using less energy by, for example, turning lights off when they are not in use. However, new types of interactions, behaviors and practices are already beginning to emerge in the context of new energy systems. We outline several such areas to consider.

Shifting energy consumption

Demand response and load-shifting are noteworthy areas in that they challenge a dominant assumption underlying how energy is currently consumed, namely that energy supply can and should always meet consumer demand. Instead of strictly focusing on conservation behaviors (using less energy), demand response is concerned primarily with *shifting* consumption behaviors to different times or places [46]. For example, while an energy conservation approach may aim to promote individuals to consolidate loads of laundry or use more efficient settings when running the automatic clothes washer and dryer, a demand response approach may aim to shift the practice of laundering from mid-day periods of high demand to nighttime or weekend periods of lower demand. Energy feedback research can play an important role in motivating and facilitating shifting behaviors. There are also opportunities to redesign individual products for integration with demand response systems. Companies are already beginning to develop DR appliances that can, for example, display changing market prices for energy or automatically respond to user defined preferences to stop or delay functions. Distributed and renewable generation also provides a very interesting context for designing shifting practices and behaviors because of its intrinsically intermittent character. Designing for shifting in this context suggests a potential reconfiguration of practices in a way that more directly relates to local weather conditions [e.g.,48,62].

Energy selection

Electricity that flows into the home and is tagged with energy metadata would allow people to know previously unknown or unconsidered characteristics of the energy they consume, such as where it was produced, how it was produced and who produced it [48]. Local distributed and renewable generation, ranging from large-scale distributed generation (such as the GridWise project) to small-scale applications (like the Peppermill and InGen) make it possible for individuals to literally see and even touch the technologies that are generating the energy they are consuming. Such contexts offer a largely unprecedented opportunity for energy consumers: selecting the type of energy or particular energy that one uses.

Sharing energy

In the future individuals and groups may not simply acquire and use energy, but additionally may be actively involved in distributing and sharing energy. For example, grid-tied homes equipped with solar or wind generation often sell power back to the electrical grid when they generate more energy than they require to meet their own energy demands. The emergence of microgrids could allow for more nuanced decisions and policies regarding how energy is shared and distributed within and between communities and households. For example, dwellers may be able to set home preferences for whether to store excess energy on-site or distribute it, and to whom. Sharing energy may also occur at the device-level. For example, microgenerated energy from energy harvesting application could be stored and shared amongst individuals, as suggested by projects like Energy Mementos and the Energy Tap.

Acquisition and adoption of energy technologies

How and why people acquire and adopt new technologies is also an important area of concern. Prior work has highlighted that current eco-feedback approaches tend to focus on curtailing the use of resources, such as curtailing hot water consumption when showering, rather than acquiring efficiency upgrades, such as acquiring a more efficient hot water heater [22]. Such efficiency upgrades have been suggested as more significant than curtailment behaviors in terms of reducing overall energy consumption. In the context of emerging energy systems, the acquisition and adoption of new technologies becomes increasingly important. For example, designers can think about ways of designing home microgeneration systems (e.g., photovoltaic) that people desire because they are fun and engaging or symbolically project important values.

Engaging with other approaches to consumption (Beyond attitude and behavior change)

Much of the energy-related HCI research we reviewed draws predominantly on theories and approaches from the fields of behavioral and social psychology. However there are many other theories of consumption developed in fields such as anthropology, sociology, geography, material culture studies, and philosophy. Several of these approaches have already seen inroads into HCI [e.g.,19,48,60,61,70]. For example, Strengers' studies of energy feedback [60,61] are interpreted through the lens of social practice theory [e.g.,56]. Practice theory offers a different theoretical perspective on how social change happens and draws attention to practices as embedded in social contexts. Consequently, Strengers' work draws attention to ways that current energy feedback technologies conflict with how people actually go about their everyday lives. The value of different theories of consumption is that they offer different ways of understanding energy consumption, and in turn focus on a range of different concerns that design can address (e.g., behavior change, self-identity, the dynamics of social systems) and types or scales of design interventions (e.g., product, service, system, policy).

Another area to consider is developing energy and consumption theory *within* HCI, rather than only applying or being guided by theory originating from outside of our field. For example, sociologists have noted the lack of rigorous theoretical engagement with energy consumption [e.g.,56,57]. Recent sociologically-informed studies of eco-feedback technologies [60,61] suggest ways such research can not only inform HCI/design but also make theoretical contributions that help explain how energy and energy technologies are (and are not) consumed. Recently there have been several works that offer design-theoretic treatments of electricity [3,49].

Engaging with energy infrastructure, service and policy (Beyond the individual consumer)

Most of the work we reviewed is predominantly focused on the individual user (and the design of product-level interventions), rather than engaging more broadly with various social groups (e.g., communities, the state), and the design of infrastructure and "behind the scenes" technologies (e.g., solar panels, water heaters), services (consisting of material and immaterial technologies), and public policy and legislation. The importance, and substantial challenges, of sustainable HCI and HCI in general moving beyond the individual has been raised previously [e.g.,15,17,29,70]. Outside of HCI there have been similar critiques of policy focused on targeting individual behaviors, attitudes and choices [e.g.,57]. These works collectively question and challenge the notion that problems of sustainability are best framed as matters of individual behavior and choice, and addressed by interventions at this level.

Although there are many interventions at the infrastructure and policy level that are largely outside the scope of HCI, there are nonetheless important opportunities to engage with these often overlooked aspects of technology design. Throughout we have suggested and demonstrated one way of engaging with infrastructure, services and policy: building upon and intervening within emerging energy systems with the design of new interactions and applications. For example, while the Energy Tap is in one sense a product for individuals to interact with, it is positioned and deployed so as to engage users and designers in a discussion around how energy is situated within public spaces.

Another important role that HCI can play is prototyping future energy applications *before* the technical infrastructure, service and policy systems to support them are fully in place. Such prototyping can serve a number of goals, including exploring, testing, and evaluating future ways of interacting with energy before they are, or can be, fully actualized. Another role that such prototyping can play is to directly inform the design and development of infrastructure, services and policy, for example, by creating compelling visions of future energy applications, interactions and practices. This type of work can take a much longer-term approach to intervention, aiming to inform technology design broadly and many years out into the future, rather than exclusively focusing on immediate applications. The extent to which HCI as a field has agency to impact policy and infrastructure is unclear, but this is a question worthy of stronger investigation.

CONCLUSION

A primary goal of this paper has been to demonstrate and advocate ways of expanding and refocusing various aspects of energy-related HCI research and design. We identified a central cluster of energy-related HCI research focused electricity consumption feedback (ECF). We further outlined a range of emerging energy technologies and socio-technical systems with strong relevance to HCI research. Based on our reviews, we outlined opportunities and challenges including new areas for ECF research as well as areas that move beyond this focus. It is our hope that this work will both further new and innovative HCI contributions, as well as further discussion within our field about the role and value of energy-related research.

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