# EnergyBugs: Energy Harvesting Wearables for Children

**Kimiko Ryokai**
UC Berkeley
kimiko@berkeley.edu

**Peiqi Su**
NYU ITP
ps2409@nyu.edu

**Eungchan Kim**
UC Berkeley
chan@ischool.berkeley.edu

**Bob Rollins**
Park Day School
bob.rollins@parkdayschool.org

## ABSTRACT

EnergyBugs are energy harvesting wearables with features that invite children to move their bodies to generate tiny, yet usable amounts of electricity. EnergyBugs not only convert children's kinetic energy into usable electrical energy, but also let children power a specially designed LED lamp with the energy the children have personally harvested. EnergyBugs therefore turn the electrical energy into a tangible object that children can manipulate and think with. Two studies of EnergyBugs with 34 elementary school children have revealed that children carefully observed and negotiated the use of personally harvested energy with their classmates, as well as developed emotional connections to energy. In particular, moving their own bodies to generate energy led the children to more actively ask questions about energy from new perspectives. We report our iterative design process and discuss the implications of our results for HCI.

### Author Keywords

Energy harvesting; children; wearable; kinetic energy; human-powered microgeneration; tangible UIs.

### ACM Classification Keywords

H.5.m. Information interfaces and presentation.

## INTRODUCTION

Sustainability and energy-conscious technologies are growing topics for HCI research. The field is concerned with the design and evaluation of systems that enable people to be more aware of their daily energy consumption habits in a variety of contexts, from personal home [e.g., 29] to workplace [e.g., 12] to public [e.g., 18], as well as how such feedback systems may lead to behavioral changes to conserve energy [e.g., 4,5]. HCI research involving energy is also explored in a variety of scales from an individual [e.g., 20], to household [e.g., 21], to city [e.g., 9].

Within this growing research area in HCI, we focus on technologies that invite people to interact with *tiny energy* (up to 3mJ per second), which can be generated by the motions of a human body. Such "human-power microgeneration" [25] produces enough energy to light up an LED for a short period of time (as with a hand cranked flashlight), but cannot power products such as a laptop. With microgeneration, the focus of interaction shifts from how much energy we *use*, to *how much energy* we can *produce* with our body. It also shifts how people understand energy from something that simply arrives from some distant source and reliably flows from the wall outlet, to something that could be "handmade" [25,24] and stored in a container. With such a shift in perspective, one may begin to (re)consider the value of energy and how one relates to energy. In particular, we see *educational* potential for engagement with microgeneration as children actively participate in the generation of their own energy and interpret their activities.

**Figure 1. EnergyBugs' energy harvesting Bugs.**

We introduce *EnergyBugs*, an experimental system consisting of a set of wearable energy-generating devices and a specially designed lamp that demonstrates how tiny, yet usable energy can be harvested from physical motion. The EnergyBugs system combines both tactile and visual engagements. Visually, the system demonstrates the energy harvesting process in real-time, and dynamically displays how kinetic energy is turned into electrical power. Through bodily and tactile engagement, we are presenting new ways for children to experience, engage with, and think about energy based on a more direct, physical, and concrete connection to the production of energy. In line with a constructionist approach of learning through construction and manipulation of personally meaningful projects [22,28], the EnergyBugs system turns *energy into tangible representations children can directly manipulate*, *personally relate to, talk about, and think with*.

We present our iterative design process, evaluations, and discuss implications for HCI.

## BACKGROUND

In response to climate change, pollution, and natural resource depletion, the HCI community has responded with a variety of approaches to address sustainability issues [14]. The majority of HCI research thus far has focused on systems that

*CHI 2014,* April 26–May 1, 2014, Toronto, Ontario, Canada.
ACM 978-1-4503-2473-1/14/04.
http://dx.doi.org/10.1145/2556288.2557225

provide electricity consumption feedback [5,20,11], often intended to persuade users to behave in a more sustainable way [7].

Recent efforts have moved beyond persuasion. Dourish [8] has argued that sustainable HCI's focus on shaping individual choices to reduce energy consumption (electrical or otherwise) can inadvertently rely on guilt around consumption as a (de-)motivating factor. Taking up Dourish's point, we argue that a crucial foundation for sustainable design lies less in prompting guilt than in prompting questions about energy as "an entity within our world, and in understanding how we use it, how we relate to it, and how we live with it" [29].

In order to understand our relationship with energy, Pierce and Paulos [25,24] have argued that we must explicitly define what we mean when we talk about energy. HCI can play an important role in prototyping future energy applications, visualizing invisibles and enabling interaction with intangibles. Yet conceptualizing *what energy means to us in our everyday context* can be difficult because energy is generally invisible and intangible. Pierce and Paulos argued that HCI and interaction design have not significantly and explicitly engaged with energy and materiality. They have suggested a variety of techniques and designs to *materialize* energy, turning energy into a material form so that we can relate to and even develop playful and emotional connections to it [e.g., 13,25,24]. Interaction with energy need not only be about utility, but may also be about critical reflection through objects at hand [1]. Our research builds on such conceptualization of energy as a physically instantiated "thing" [25,24]. Here we apply the concept in the context of children's interaction with energy.

We also draw inspiration from recent research, which suggests that interactions and experiences which require *less* energy can be more pleasurable, enjoyable, and meaningful. For example, Håkansson and Sengers [16] studied families who have voluntarily chosen to "live simple" and found that families were not driven by details about *how much* energy they consume in everyday life, but positively motivated, by being satisfied with what is *enough.*

In particular, Pierce and Paulos' work on "human-power microgeneration" has inspired our research. Pierce and Paulos [25] introduced the term "human-power microgeneration" to designate the microgeneration of electrical energy from human energy sources, with an emphasis on bodily, kinetic energy. Human-powered microgeneration is energy generation at its smallest and most personal scale (up to 75W = 1 human unit of power [25]): electricity that can be generated *by hand*. Through their design explorations, Pierce and Paulos described a variety of human-electricity relations and explored diverse elements of energy consumption as an intentional, embodied entity. However, it is important not to confound human-powered devices as a reliable solution to world-wide energy depletion. For example, Wyche and Murphy [33] illuminated a mismatch between the real-world conditions of developing countries and Western designers' good intentions. Many of the HCI human-powered electricity design explorations are not meant to effectively bridge the electricity gap between the affluent urban energy consumers and that of rural areas. The primary goal of these design explorations is to investigate educational and transformative aspect of human-power microgeneration.

Epistemologically, making energy "by hand" and thinking about the very act, fit well with the constructionist tradition of learning by doing. In the constructionist approach, learning happens when a person is actively engaged in construction of meaningful objects in the real world [23,22,28]. Knowledge is not transmitted, but rather (re)constructed through active involvement. We see human-powered microgeneration as a constructionist educational opportunity. Materializing energy in a tangible form allows children to actively engage in the making process, and think about what they are doing as they do it. Rather than informing children how energy *is* or *should be* used, turning energy into a *manipulable* material invites them to take ownership over the concept through personal, engaged reflection.

### Technologies for Children to Learn about Energy

While the constructionist approach has been applied to many different types of tangible educational tools in HCI [e.g., 28,26,35, just to name a few], applying tangibles to children's interaction with energy within HCI is a relatively new area [e.g., 6,15]. Exceptions are the games by Johansson et al. [17] and Zhang et al. [34]. In both games, children explore different types of energy and energy consumption through their embodied performances tracked by body-worn motion sensors. However, both games are educational simulations; they do not actually harvest kinetic energy from children's physical movement.

Outside of HCI, hands-on museums such as San Francisco's Exploratorium host exhibits that demonstrate kinetic energy interactively. Our work builds on such interactive exhibits, but makes the activities even more personal by creating wearables that can exist in children's personal environments. Our research involves treating actual energy as a personal manipulable. The focus is on creating a tangible artifact for the *quantity* of energy, not just the flow of energy, and not through simulation, but through actual energy generation and use of energy.

### Related Technologies

We have reviewed different types of human motion based energy harvesting technologies. "Parasitic Power Shoes" [30] is a classic example that uses piezoceramic composite material to generate electrical energy "parasitically" while walking. Paradiso and his colleagues have also created a version with a shoe-mounted rotary magnetic generator [19]. Today, we see efforts to turn these research prototypes into commercial products. For example, *SolePower* [31] aims to manufacture waterproof shoe insoles with energy harvesting mechanical links and crank-style generators inside. *ReRev* [27] is a commercial service that retrofits exercise equipment (such as elliptical machines) into electricity generating machines. *Fenix International* [10] sells bicycle attachments for a portable energy generator set designed for use in developing nations. One hour of pedaling generates approximately 45 watt-hours. The Figure 2 compares our technology to other energy harvesting technologies.

In contrast to these commercial products, our contribution is not aimed at efficient energy harvesting technology. Rather, we are designing technology to support energy generation at its smallest and most personal scale, through a small object children can hold in their hands (c.f., Villar & Hodge's Peppermill [32], Badshah et al.'s InGen [2], and Pierce & Paulos' Energy Memento [24]). We ask how such human-powered microgeneration influences the relationship children may have with energy.

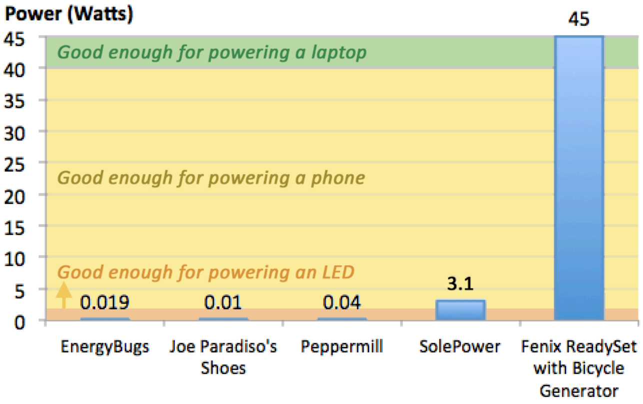


**Figure 2. Graph showing where our technology places in the landscape of other energy harvesting technologies.**

## ENERGYBUGS

We created the *EnergyBugs* system to invite children to directly engage with and to be the creators/generators of personal energy. The goal is to make the interaction with energy 1) *bodily* and *tactile*, 2) *portable* (so that they can take it anywhere) and 3) *visible* (the connection between the bugs and the lamp is made visible as are the energy resources and the energy flow).

The EnergyBugs system has two parts: the energy harvesting "Bugs" and the "Lamp" that can be powered by the harvested energy from the Bugs (Figure 3). The *Bugs* are wireless self-powering units with dual energy generators inside. Each time a Bug is physically shaken, a magnetic cylinder in the Bug moves back and forth causing the outer coil to generate energy. When piezoceramic disks on each end contact the magnetic cylinder, they generate additional energy upon impact. Vigorous shaking results in a fast charge and gentle shaking results in a slow charge. The harvested energy is used to power the Lamp as well as to power the Bug itself. For example, if a child shakes the Bug for one minute, the Bug generates approximately 0.66J, which is enough to power the Lamp for 50 seconds as well as to power the microprocessor inside for 180 seconds. Data regarding how much energy harvested relative to how much the Bug was shaken is also recorded, enabling kids to track how much energy they have collected over time. This analytic data and energy can be transferred when the Bug is connected to the Lamp's base station. We describe the technical implementation further in the following section.

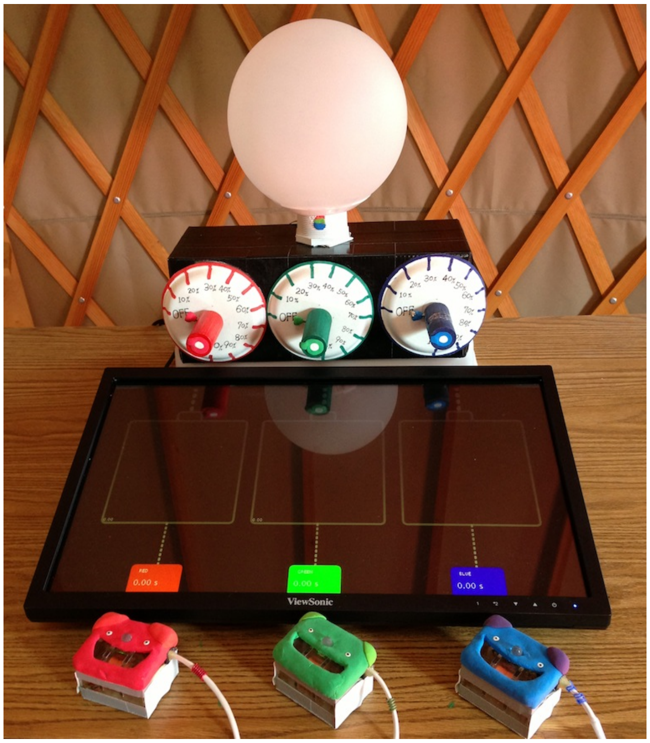


**Figure 3. EnergyBugs system with energy harvesting Bugs, display, and the Lamp.**

The *Lamp* is powered only by energy from one or more EnergyBugs. When the Bugs are connected to the Lamp's base station, the display shows how much energy each Bug has harvested as well as how long the harvested energy can power the Lamp. (Figure 3 & 4) When the energy from the Bug runs out, the Lamp goes dark. The more energy is harvested, the longer the Lamp remains lit. The Lamp also has dimmers, allowing children to vary the levels of brightness. The dimmers demonstrate in real time that a brighter light consumes more electricity. The display also shows the countdown to give children the sense of energy "burn rate." For example, at full brightness, the energy is used at 45mJ/second, while at the mid brightness it is only 11.25mJ/second. The display shows the number of seconds left before the energy is expended.

In our current system, up to 6 Bugs can be plugged into the Lamp simultaneously. When the Bug is shaken while it is plugged into the Lamp, the display shows the harvested energy value in real time. When the Bug is disconnected, the value is stored inside the Bug and shown when it is plugged into the Lamp.

The Bugs are color coded red, green, and blue (RGB). All Bugs function identically, except at the Lamp base station the Lamp illuminates with the Bug's corresponding color (i.e., the red Bug turns the Lamp red). Three dimmers at the base of the Lamp (Figure 3) control the intensity of individual colors in order to mix them.

## Design and Technical Implementation

### *Bugs*

The Bug implements two energy harvesting methods: 1) the electromagnetic method and 2) the piezoelectric method in collecting kinetic energy.

*The Electromagnetic Energy Harvesting Subsystem* of each Bug houses a rare-earth magnet (neodymium magnet) inside a clear acrylic tube in the middle of the box. Each tube has two 1500-turn coils: one is for generating usable energy to power the lamp; the other is to power the whole circuit (Figure 4). One coil with a 5494 surface Gauss neodymium magnet generates approximately 9.5 mW when users shake the bug. This energy, stored in a 0.6 Farah super capacitor, powers the lamp. Stored in a 0.4 Farah super capacitor, it powers the circuit. Customized hardware minimizes both the energy consumption of the circuit and the size of the Bug.

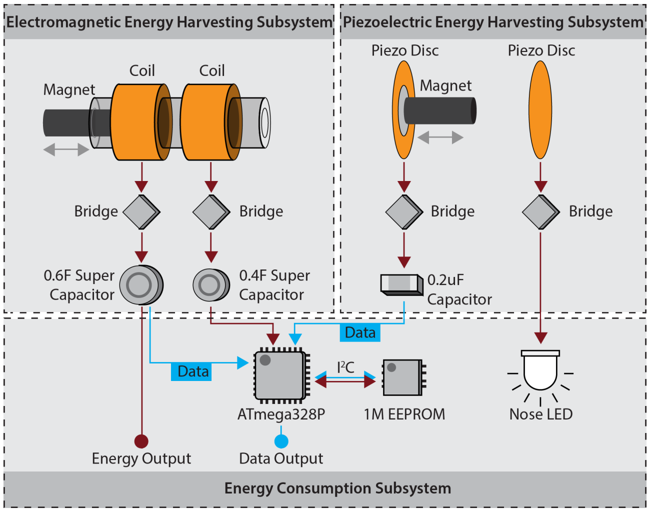


**Figure 4. EnergyBugs' dual energy harvesting system.**

*The Piezoelectric Energy Harvesting Subsystem* contains two piezo discs that serve as sensors. The voltage output of one disc triggers a 10mm white LED (the Bug's "nose"), while the other senses user movement data (Figure 4). As a user shakes a Bug, the magnet first hits one piezo disc to flash the nose LED, then hits the disc on the opposite side to generate a voltage reading which is logged into the EEPROM. The system can then visualize this movement data later.

We designed the box of the Bugs to be transparent so that children can see the inner mechanisms of the generator and other electronics. To make it look friendly, we dressed up one side of the box with a character face. The mouth of the Bug acts as a window enabling children to see the mechanisms inside. A blinking "heart beat" LED, visible through the Bug's transparent body, indicates that the system is on. The Bugs are small and they are wireless so children may run around without any tether. In wireless mode, a modified *GoPro* wristband attaches the Bug to an arm or leg.

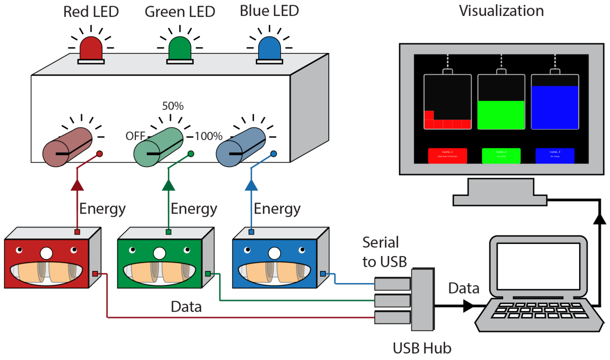


**Figure 5. EnergyBugs system diagram.**

### *Lamp*

RGB color mixing invites children to experiment with consuming the harvested energy at different rates.

The RGB LED's color-mixing system utilizes a 555 oscillator to convert the analog values from the potentiometer to Pulse Width Modulation (PWM) signals, which enables the LED's brightness to change smoothly and uniformly. Bugs can be plugged with a DC power cable into a 1.35mm power jack on the Lamp. After a Bug has been plugged in, a DC converter steps up input voltage from the Bug's 0.6 Farah super capacitors to 3.3 volts, which allows the lamp to work in full voltage input range. The RGB LEDs are housed in a large diffuser (Figure 3).

## Pilot Study with first EnergyBugs prototype

We conducted a pilot study to test our interaction design and the robustness of our system. Our pilot studies took place at two different summer camps in the San Francisco Bay Area. A total of 16 children ages 6-13 participated in the pilot studies (8 children [ages 6-13] at camp A at a public program and another 8 children [ages 6-11] at camp B at a private school). Both groups participated in the pilot study during their regular summer camp hours. The children played in groups of 2-3. In the first 5 minutes, researchers explained the system to the children. In the beginning of the session, the EnergyBugs were connected to the Lamp and display so that researchers could demonstrate how EnergyBugs harvest the energy in real time. After the children explored EnergyBugs for a few minutes, they were then told that their Bugs could be wireless and that their Bugs would still "remember" how much energy had been generated. The children were invited to play as long as they wished.

### *Interaction with the Bugs: Energy Harvesting*

The children spent an equal amount of time working with the Bugs in the wireless mode and the wired mode in front of the Lamp. In wired mode the children could monitor their energy harvesting progress in real time. The children saw each other's progress side by side.

Though we carefully avoided describing the activity as a "game," the side-by-side display of their real time energy production often resulted in the children competing against each other. Upon seeing one's energy level exceeding another's, children exclaimed, "In your face!", "I beat you!", etc. The children also wanted to fill the battery with their energy "all the way up." Some children told their friends, "Whoever gets to the top first is the winner!" Without being told what to do with EnergyBugs, the children defined their own activities, set goals, and challenged each other to competitions.

The children shook the Bugs vigorously, but also experimented with different types of shaking (e.g., fast, slow, strong, soft, different angles, etc.). The tactile feedback of the unit (physically feeling the weight of the heavy magnet move from one side to another) and the sound of the magnet hitting the piezo disks each time, provided acoustic and kinetic feedback.

The children moved around the room with the Bugs first, trying out different moves, positions, and even dances. As soon as the children found out that the Bugs could be unplugged, they wanted to go outside the study room and run around with the Bugs. While in wireless mode, the older children (age 8 and up) worked with the Bugs in a variety of manners. Some of the older children attached the wristband to their legs allowing them to move faster or try different types of movements with their body. The older children also tried different combinations of shaking relative to their body movements. For example, one 10 year old told us "It works better if I shake it this way while I'm running around."

**Figure 6. Children working with EnergyBugs.**

Many children were curious about how the technologies inside the bug worked. The transparent case allowed children to see the mechanisms inside (e.g., the magnet moving inside the coil and the accompanying electronics), prompting many children to ask researchers questions about the technology inside. Many children told us that they liked that the Bug's "heartbeat," indicated the unit was working even during the time it was unplugged.

### *Interaction with the Lamp: Energy Consumption*

At the beginning of each session, we showed the children how the Lamp worked, but did not tell them how they should play with the lamp. The children figured out on their own that they could control multiple LEDs at varied brightness simultaneously, and as a result, they could create different colors. We purposely did not tell the children that they had to use up their harvested energy. We also did not tell them that if they ran out of the energy they had to collect more. The children decided independently when they should collect more energy or when they should use their energy. In going through the cycles of harvesting energy and using their energy, the children in all age groups developed a personal attachment to "their" energy. Quite often they were protective of their own energy and unwilling to share it with other students. For example, upon seeing another child trying to use one's energy, a child yelled, "It's *mine*!" and another, "Don't you dare touch mine!" Yet creating different colors other than red, green, and blue meant that they had to share some of their energy and collaborate. Seeing colors other than their own was sometimes sufficient motivation for children to share their energy with others, and rewarded them with the outcome, e.g., "Wow, I like that purple!" For the children, the trial often seemed like a balancing act. They worked hard to get their own energy, but had to negotiate and collaborate with other children for more interesting effects.

### *The Mattering of Microgenerated Energies*

The word choice of the children when describing EnergyBugs revealed a sense of care and ownership for the energy created. For example, upon seeing a lamp accidentally left on, children quickly informed each other, "You are *wasting* your energy!" By pointing at the lamp and its display showing decreased energy, some children said, "It's *eating* my energy!" When another child had accidentally turned on their energy, a few children even said, "You wasted *my* energy! I *worked very hard* for that!" The children also showed a sense of accomplishment towards their work and felt protective about the energy as a reflection of their hard work. One child yelled at another child, "Don't touch it! It's *my history*!"

The kind of care the children showed towards their energy and the vocabulary they used in talking about energy were similar to what Pierce and Paulos found in their studies with "Energy Mementos," where energy *mattered* to people because *"they made it themselves"* [24,25].

The quantities of energy children obtained from EnergyBugs were tiny compared to what they could get from a regular battery or wall plug. So why did the energy "matter" and "hold significance" to the children? One explanation is the engagement with human-powered microgeneration: if one has to work hard for energy and get so little energy in return, one may increase one's sense of care and appreciation towards energy.

Another explanation stems from the way EnergyBugs made energy tangible and personal: because individual children were able to hold onto and claim it their own, they cared for it. This required further investigation, and motivated our second study.

## SECOND STUDY

The goal of our second study was to investigate whether or not the type of children's behaviors observed in our first study, i.e., curiosity, care, and empathy towards energy, were due to microgeneration in the EnergyBugs system. In order to empirically study this, we conducted the second study where we manipulated the presence and absence of microgeneration between two groups.

#### *Age Appropriateness*

In our pilot study we observed that children in a wide age range enjoyed working with our system. However, the children under age 9 seemed too young to grasp the concept that EnergyBugs were producing energy, and not just accumulating points in the battery display. According to the current California State Board of Education Science Content Standards [3], by grade four, children should "know the role of electromagnets in the construction of electric motors, electric generators, and simple devices, such as doorbells and earphones." Therefore, we decided to work with fourth graders in an elementary school in our second study.

### Methods

#### *Participants*

Eighteen children ages 9-10 participated in the study. All children (12 girls and 6 boys) were enrolled in a fourth grade classroom in a private elementary school. The children were randomly assigned to two groups, using a system that resulted in consistent gender distribution so that each group consisted of 2 girls and 1 boy.

#### *Materials and Procedure*

We designed a between-subject study wherein the experimental group played with the EnergyBugs and the second group played with a "plug-in" version of EnergyBugs. The "plug-in" Bug was designed to appear exactly like the EnergyBug, but acted like a rechargeable battery. It could be directly plugged into the wall and fully charged within 2 minutes (the nose LED would light up after 2 minutes to indicate the charge status). We concluded that this was an appropriate condition to compare, as many current wireless devices work this way (people do not usually physically exert themselves for energy). Our primary goal was to vary the presence or absence of human-powered microgeneration between the two groups. Otherwise, both groups had the same activity of using their energy to light up the Lamp and mix colors. The difference was that the EnergyBugs group had to work physically hard to acquire the energy while the plug-in group did not.

Prior to the activities, all 18 children received a 20-minute lesson from their usual classroom teacher about different types of energy and energy harvesting techniques such as solar, wind, and water by using everyday examples (e.g., solar powered calculators, water mills, etc.). This lesson provided context for the subsequent activities of both the EnergyBugs (EB) group and the plug-in (PI) group.

Immediately after the 20-minute lesson, all children were asked to fill out a survey about energy. The survey was designed jointly by the research team and the fourth grade teacher (4th author) with reference to the Science Framework for California Public Schools [3]. The questions were designed to probe the children's attitudes towards energy use as well as their curiosity for energy, and were open-ended (rather than yes/no) to elicit maximum input from children. After the survey, the children worked in groups of three with either EnergyBugs or "plug-in" version of EnergyBugs for 30 minutes. The two groups, EB and the PI group, were isolated from each other. After the 30-minute intervention, we repeated the same survey so that we could observe whether or not the intervention influenced the children's attitude towards energy. We ended each of the 6 groups' sessions with a semi-structured interview about their experience working with EnergyBugs. To ensure that the interviews were consistent, we used a script comprised of three questions: "How do you like EnergyBugs?" "What do you not like about EnergyBugs?" and "Outside of school, how might you use EnergyBugs?" During the study, researchers carefully monitored word choice to avoid influencing the children's vocabulary. All the sessions were video recorded so that we could transcribe the children's dialogue and analyze their physical interaction with the system.

### Results

Both the EB and the PI groups spent equal amounts of time engaging with their respective systems. Both groups began in the school's computer lab, and they were free to move around both inside and outside the room. Yet, there were clear differences between the two groups in their physical activity levels during the 30 minutes. As predicted from the pilot study, as soon as the EB group members found out that they could unplug their Bugs, they wanted to go outside and run around. Similar to the pilot testing, the EB groups spent a third to half of their time running around outside.

EnergyBugs being a wearable device seemed to encourage different types of engagements. Physically, the EB group members explored many different ways they were able to generate energy. At the end of each session, the EB group members were breathing hard and covered with sweat.

In contrast, all three PI groups remained inside the computer lab, even though they were free to go anywhere they wanted. They found wall outlets inside the computer lab. They seemed content using them and did not appear to see any point in moving outside the lab. In contrast to the EB groups, the PI groups spent their time patiently waiting for their plug-in Bugs to be ready.

Because of these anticipated activity level differences, we were concerned that the PI group would not enjoy their devices as much as the EB group. However, all three PI groups wanted to continue playing with their Bugs even after the allotted 30 minutes. In the post-study interview, we heard similar reports from children in both PI and EB groups indicated that their activity was "Awesome!", "Cool!", and "Really fun!"

**Figure 7. A child practices basketball while a Bug is attached on his wrist (left). Children attaching Bugs on their legs prior to running (right).**

### *Vocabulary for Energy: Mattering of Human-Powered Microgenerated Energies*

From our pilot study, we anticipated that the energy would matter to the children in the EB groups because they personally harvested it from their own physical efforts. But how about the PI groups who did not physically work as hard (relative to the EB groups) to generate their own energy via human microgeneration? Using transcripts, we analyzed how children in each group described energy. We used Pierce and Paulos' framework of "materializing energy" [24], treating energy as a tangible manipulable "thing" that can be 1) *shared*, 2) *activated*, 3) *kept*, and 4) *collected*. For both groups, we tallied the occurrences of keywords within these four categories. Table 1 summarizes the number of occurrences in each group.

The language the children used in both the PI and the EB groups were more similar than we had predicted. The children in both the PI and the EB groups felt strong ownership over their energy. When their classmates tried to use their energy without asking, the children clearly indicated it was unwelcome by yelling, "No!" or "That's mine!" and sometimes physically thrashing their hands. Yet, children in both groups eventually managed to "borrow" others' energy by asking before touching their dimmers.

Children in both the EB and the PI groups used a similar vocabulary for describing how their energy was being used. The occurrence of words such as "wasting," "losing," "going fast," and "emptying" was similar across groups. Both EB and PI groups therefore, in interaction with EnergyBugs system, seemed to perceive and describe energy *use* as a somewhat negative event. Using energy was an event of energy retreating (going negative) as opposed to an event of activation (powering the Lamp). This was interesting because the EnergyBugs visualization, in both the EB and PI groups, showed the Lamp being activated by their energy. We believe the Lamp's numerical indication of energy level going up and down in real time elicited this interpretation.

| | Plug-in Group | EnergyBugs Group |
|---|---|---|
| **Sharing** energy (distributing) | "It's **mine**!" (7)<br>"Could you give me **permission** (to use the energy)?" (3)<br>"Don't even think about it!" (2) | "It's **mine**!" (8)<br>"Can I **borrow** yours?" (5)<br>"**Don't touch**!" (3) |
| **Activating** energy (using/consuming) | "You're **wasting** your energy" (5)<br>"**Using up** all my energy!" (4)<br>"You **lose** it (energy)…" (3)<br>"It **goes away** real fast when it's at 100% (brightness)" (3) | "You've just **wasted** energy!" (4)<br>"I'm **using up** my energy" (5)<br>"I'm **losing** my energy" (4)<br>"**Going away** very fast!" (3) |
| **Keeping** energy (storing/ maintaining) | "I'm **saving** my energy" (5)<br>"**It's at** …" (6)<br>"I'm **going to save** my energy so that when I go back…" (3) | "I'm **saving** my energy" (6)<br>"Mine **is at** 3 and yours is…" (5)<br>"I'm going to **keep** mine at ..." (4) |
| **Collecting** energy (generating/ producing) | "Woo! All **done**!" [looking at the charge indicator] (9)<br>"Mine **isn't (done)**" (8)<br>"Let me go **unplug** mine" (5)<br>"Going to **charge** mine" (3) | "**Worked** so hard for this!" (8)<br>"Mine is **growing**!" (8)<br>"OMG you **have so much**!" (7)<br>"**How** do you get so much?" (6)<br>"I'm **making** energy!" (6)<br>"I'm **shaking** it really hard!" (5)<br>"My hard work paid off finally!" (1) |

**Table 1. Occurrences of keywords summarized for the Plug-in group and the EnergyBugs group.**

Both EB and PI groups indicated their wish to save or sustain their energy at certain level (e.g., "I'm *saving* my energy!" "I'm keeping mine at 3.5!"). When they saw their energy level went down, they wanted to fill it up again. Both groups noticed that different levels of brightness produced different energy burn rates. Both groups hesitated equally before using up their energy all at once. Rather, they wanted to carefully control how their energy was being used. Dimmer controls with immediate feedback seemed to invite explicit monitoring of the Bugs' energy level. Both groups also monitored and talked about numerical energy levels relative to their peers, e.g., "I'm at 1.4 and you are at 1.5."

A primary difference between the groups was the manner in which EnergyBugs group members discussed the process of their energy making. The EB group often mentioned physically working hard (e.g., "I'm working so hard!" "I'm sweating!"), and acknowledged others' accomplishments (e.g., "Wow, you've got so much!"). The EB group members also asked each other about techniques for collecting energy (e.g., "How are you getting so much energy?") and showed each other their physical movements. Physical and acoustic rhythm of children's shaking seemed to influence each other. When one of the children sped up their shaking, other children tried to catch up with the faster pace. While they were shaking their Bugs, the EB group children also spontaneously asked researchers questions such as "Can I use this in my room?" "Can I charge an iPad with this?" and sometimes responded to their own questions such as, "Wow, I would have to work very long time for that!"

For the PI group, talk around the energy collecting process was minimal and typically took the form of an announcement of the beginning and/or end of the charging ("I'm going to charge again"). During the 2-minute charging times, they were either quiet or talked amongst themselves about topics unrelated to EnergyBugs (e.g. homework, other friends).

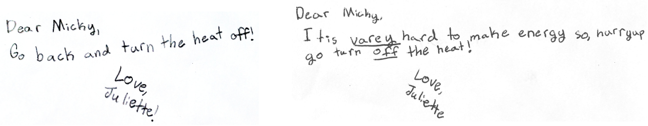
In summary, from the children's language use, energy seemed to *matter* to both groups equally when it comes to *sharing*, *activating*, and *keeping* energy. Both groups interpreted *ownership* of their energy and its use in similar ways. However, microgeneration did engage children in more explicit discussions around energy *collecting* and *making* process and led them to ask more questions about energy production and real-world energy use.

### *Concern for energy use*

Did children's interaction with EnergyBugs influence their attitude towards energy use in general? This question in the pre- and post-test survey aimed to evaluate such general attitudes:

Pretend someone named Micky turned the heat way up in the building on a Friday in the winter. Micky went home and realized that he had forgotten to turn down the heat. He knew that a lot of energy would be used keeping the building very warm all weekend. But he was having a great time playing with his friends and didn't want to go back to school and turn the heat down. Please write a one-sentence note to Micky.

We compared the children's answers before and after the intervention. In the pre-test survey, all children in both groups wrote text indicating that Micky should go back and turn the heat off. This pattern suggests that all of the children in our study were already energy conscious to some degree prior to their exposure to EnergyBugs. In the post-test survey, all children's responses remained the same. They wrote the similar text indicating Micky to go back and turn the heat off. Across groups, their answers did not change before and after the intervention. What was different between the PI and EG groups, however, was that the EB group expanded their answers in the post-test survey. In the EB groups, 4 of the 9 children provided additional reasons for Micky (e.g. "to save *more* energy," "very hard to make energy") in contrast to 1 out of 9 in the PI group.



Dear Micky,
Go back and turn the heat off!
Love,
Juliette!

Dear Micky,
I tis varey hard to make energy so, hurryup go turn off the heat!
Love,
Juliette

Figure 8. One child's answer before (left) and after (right) the intervention.

### *Asking Questions Differently and More Lessons*

We were interested in finding out whether the interaction with EnergyBugs led to increased curiosity towards energy and how things work with energy. In the survey, we asked how much the children wanted to learn about energy:

How many more lessons about energy do you hope we do this year? (0 - 10)

We compared the children's answer before and after the intervention. The average score for both groups were initially similar (average score of 4.1 for the EB group and 4.5 for the PI group). The EB group members, after the intervention, indicated that they would like to have more lessons about energy significantly more than the PI group; t(16)=2.55, p=0.021. According to our post-test interview, both EB and PI groups equally enjoyed their activities with respective version of EnergyBugs. Then why did the EB group want to have more lessons than the PI group? How the children responded to the following questions in the survey seems to explain this:

An energy expert may come and would want to know what the class would like to learn more about and what the class is wondering. Please write a question for the experts.

We compared what children wrote before and after the intervention. Before the intervention, children from both groups asked about the origin of energy (e.g., "Where does energy come from?"), how is energy made (e.g., "How … ?"), and specific technical questions (e.g., "Can you use solar panel to power an iPod?"). After the intervention, 6 out of 9 children in the EB groups asked different questions (e.g., "Can you *see* electricity? When and who invented electricity?" "How (does) 'moving a lot' make energy?" "How do you (PG&E) make *so much* energy?"). In contrast, 8 out of 9 children in the PI groups repeated exactly the same responses they made previously in the post-test.

Similarly, we asked the following question in the survey:

Our electricity company ("PG&E") has two big coal-burning electricity plants that have to be closed down because they are old. PG&E won't be able to generate enough electricity for all their customers after the two plants are shut down. Please write a suggestion for PG&E.

Before the intervention, about a third of the children in both groups wrote, "I don't know" (4 children in EB group and 3 children in PI). The children in both groups responded that either the plants should be fixed (e.g., "Fix the plants") or resort to other technologies (e.g., "Buy solar panels"). After the intervention, 6 out of 9 children in the EB group changed their response (e.g., "Sell people things they can make their own energy!" [emphasis inserted by the child], "… find out what's wrong!" "… find *other ways* to *create* electricity"). In contrast, as with the previous questions, 8 out of 9 children in the PI group repeated exactly the same responses they made previously in the post-test.

The children's answers to the open-ended questions in the survey suggest that the experience of human-power microgeneration seemed to encourage children to ask questions regarding energy more actively or from a different perspective than they had before.

## Discussion

The results of our study revealed that human-powered microgeneration activities can enhance and increase curiosity in children, can prompt them to more actively ask questions about energy harvesting and energy in general, and can lead children to want to participate in subsequent lessons about energy. Compared to the PI group, the children working with EnergyBugs directly experienced how energy could be harvested through physical activity. Such exposure to novel experiences seemed to engage children to consider why things work the way they work, or question things they may not usually question (e.g., "Can you *see* electricity?" or how would "so much energy" be created by an energy company?). Therefore, microgeneration seems to be an effective way to encourage children's curiosity and learning about forms of energy and their production.

The results of our studies also revealed that all children working with EnergyBugs, whether they physically exerted themselves to generate the energy or not, *cared* for their energy. The way energy *mattered* to the children (i.e., how they related to energy personally by protecting their own energy, and how conscious they were in using their harvested energy) did not seem directly influenced by the experience of human-powered microgeneration.

One possible explanation is that, in a way, both the EB and the PI groups *worked* for their energy. The EB group worked physically harder, but the PI group children also worked for their energy by patiently waiting for their Bugs to be charged each time they wanted energy. The feeling of "*I* made this" seemed to be the same for both groups, even though *how* they made it was different across the two conditions.

Another possible explanation is the representation the EnergyBugs system used to make energy visible and tangible for children. Both EB and PI groups were able to *hold* a physical representation that stood for energy in their hand, connect the Bug to the Lamp and physically control how their energy was used. This made it visible to children, and gave them a concrete way to talk about, play with, and have a personal relationship with energy. One may compare a scenario of a child playing with a regular battery: The child connects a battery to a toy train and the train moves. The battery is a tangible object the child can hold in her hand, but the object does not typically allow her to see the content (quantity of energy) nor allow her to control how the energy flows into the battery and out to the toy. Therefore, the EnergyBug's design to turn energy into a manipulable and tangible form, inviting children to play with and relate to, was a successful way to engage children.

Through our iterative evaluation of EnergyBugs with children, we were able to tease out some important aspects of human-powered microgeneration and how it might influence the way children interact with and think about energy. It is difficult to separate the actual microgeneration production process from the representations we designed for that process, and to study how they are perceived by children and people in general. Both the product and process of microgeneration need a perceivable representation so that people can relate to it with their bodies. We have increased appreciation for energy through the experience of microgeneration, but is it because the energy is manifested in such a small and unexpected way? Or is it because it is difficult to generate electrical energy by using human body? What does it mean to feel like one "worked for" the energy? Even though we have some answers, our research opens up follow-up questions about human-powered microgeneration that will be relevant for future HCI research that deals with energy.

## LIMITATIONS & FUTURE WORK

We are currently making a number of improvements to the system. For example, our next iteration is capable of powering up other devices including commercial mobile devices.

We also are preparing to conduct a study where children will be invited to play with EnergyBugs while we observe their activities in a longer time frame, over multiple days and even weeks. More specifically, we are interested in analyzing children's activities over time relative to the quantity of energy. In addition, our evaluation of what children actually learned about energy harvesting technology was limited to the pre- and post-test surveys. We are currently working with elementary school teachers to design more targeted science lessons involving energy harvesting mechanisms inside the Bugs.

Finally, we note that EnergyBugs encouraged physical movements from children voluntarily in different manners (running, dancing, etc.), at a variety of indoor and outdoor locations. While it was not the focus of the current research, future design research might combine physical exercise and science learning, as childhood obesity continues to be a problem in the United States. Systems such as EnergyBugs could simultaneously encourage physical exercise and engaging children in relevant scientific topics. EnergyBugs could be a technology that encourages physical exercise while engaging children in relevant scientific topics.

## CONCLUSION

Energy can seem like an abstract and distant concept to both children and adults. In contrast to informing children what energy is and how energy is used in the typical fashion, we took a constructionist approach of engaging children directly in the energy harvesting process—not through simulation, but through the production of tiny, yet usable energy from the motion of their bodies.

Two studies of EnergyBugs with 34 elementary school children revealed that such microgeneration through bodily movements invites children to discuss their energy making process more explicitly, and to more actively ask questions about energy from new perspectives. Emotional attachment to one's energy however, came from the EnergyBug's design to materialize energy in a way children can directly interact with, not whether producing the energy required physical labor. This highlights the important role interface design can play in making abstract concepts concrete and personal for children.

## ACKNOWLEDGMENTS

We thank all the children and their parents who have participated in our study at Park Day School, Camp 510, and Emeryville Recreation Center. Our special thanks go to Deqing Sun for his boundless support. We thank Yoon Jeong, James Pierce, Eric Paulos, Laura Devendorf, Elizabeth Goodman, Brian Carver, and Stefan Marti for their help and invaluable discussions.

## REFERENCES

1. Backlund, S. et al. 2006. Static! The aesthetics of energy in everyday things. Proc. of DRSIC.
2. Badshah, A., Gupta, S., Cohn, G., Villar, N., Hodges, S., Patel, S.N. Interactive Generator: A self-powered haptic feedback device. Proc. CHI '11.
3. California State Board of Education. http://www.cde.ca.gov/be/st/ss/
4. Darby, S. 2001. Making it obvious: Designing feedback into energy consumption. In Proc. CEEHA. Springer.
5. Darby, S. 2006. The effectiveness of feedback on energy consumption. A review for DEFRA.
6. Desjardins, A. & Wakkary, R. How children represent sustainability in the home. In Proceedings IDC'11.
7. Disalvo, C., Sengers, P., Brynjarsdottir, H. 2010. Mapping the landscape of sustainable hci. In CHI'10.
8. Dourish, P. HCI and environmental sustainability: the politics of design and the design of politics. Proc. DIS '10.
9. Erickson, T., Li, M., Kim, Y., Deshpande, A., Sahu, S., Chao, T., Sukaviriya, P., & Naphade, M. The dubuque electricity portal: evaluation of a city-scale residential electricity consumption feedback system. In CHI '13.
10. Fenix International. http://fenixintl.com
11. Fitzpatrick, G. & Smith, G. 2009. Technology-enabled feedback on domestic energy consumption: Articulating a set of design concerns. IEEE Pervas. Comput. 8, 37–44.
12. Foster, D., Lawson, S., Wardman, J., Blythe, M. & Linehan, C. 2012. "Watts in it for me?": design implications for implementing effective energy interventions in organisations. In Proceedings CHI '12.
13. Gaver, W., Bowers, J., Boehner, K., Boucher, A., Cameron, D., Hauenstein, M., Jarvis, N., Pennington, S. 2013. Indoor weather stations: investigating a ludic approach to environmental HCI through batch prototyping. CHI '13.
14. Goodman, E. 2009. Three environmental discourses in human-computer interaction. In CHI '09 EA.
15. Grufberg & Jonsson. Sciensations: making sense of science by designing with sensors. IDC'12
16. Håkansson, M. and Sengers, P. 2013. Beyond being green: simple living families and ICT. In Proceedings of CHI '13.
17. Johansson, C., Ahmet, Z., Tholander, J., Aleo, F. Weather Gods and Fruit Kids - Embodying Abstract Concepts Using Tactile Feedback and Whole Body Interaction. CSCL2011.
18. Johnson, L., Broms, L. & Katzeff, C. 2010. Watt-Lite:Energy Statistics Made Tangible. DIS '10.
19. Kymissis, J., Kendall, C., Paradiso, J., Gershenfeld, N. 1998; IEEE Conference on Wearable Computing.
20. Mankoff, J., Matthews, D., Fussell, S. R., Johnson, M. 2007. Leveraging social networks to motivate individuals to reduce their ecological footprints. In HICSS'07.
21. Neustaedter, C., Bartram, L. & Mah, A. 2013. Everyday activities and energy consumption: how families understand the relationship. In Proceedings of CHI '13.
22. Papert, S. (1980). Mindstorms: Children, Computers, and Powerful Ideas. New York: Basic Books.
23. Piaget, J. (1972). The Principles of Genetic Epistemology. New York: Basic Books.
24. Pierce, J. and Eric Paulos. 2010. Materializing energy. In Proceedings of DIS'10.
25. Pierce, J. and Eric Paulos. 2012. Designing everyday technologies with human-power and interactive microgeneration. In Proceedings of DIS '12.
26. Raffle, H., Parkes, A., Ishii, H. Topobo: a constructive assembly system with kinetic memory. Proc. CHI '04.
27. ReRev. http://rerev.com
28. Resnick, M., Martin, F., Berg, R., Borovoy, R., Colella, V., Kramer, K., Silverman, B. 1998. Digital manipulatives: new toys to think with. In Proceedings of the CHI '98.
29. Schwartz, T., Denef, S., Stevens, G., Ramirez, L., & Wulf, V. Cultivating energy literacy: results from a longitudinal living lab study of a home energy management system. In Proceedings of CHI '13.
30. Shenck, N. & Joseph A. Paradiso. "Energy Scavenging with Shoe-Mounted Piezoelectrics," IEEE Micro, Vol. 21, No. 3, May-June 2001, pp. 30-42.
31. SolePower. http://solepowertech.com
32. Villar, N. & Hodges, S. 2010. The Peppermill: A Human-Powered User Interface Device. Proc. TEI'10.
33. Wyche, S.P. and Murphy, L.L. (2013). "Powering the Cellphone Revolution: Findings from Mobile Phone Charging Trials in Off-Grid Kenya," Proc. of CHI'13
34. Zhang, Z., Shrubsole, P., & Janse, M. 2010. Learning Environmental Factors through Playful Interaction. IDC.
35. Zuckerman, O., Arida, S., Resnick, M. 2005. Extending tangible interfaces for education: digital montessori-inspired manipulatives. In Proceedings of the CHI '05.