Lovable Sustainability:
From Residential Solar PV Systems to Eco-Feedback Designs

by

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Abstract

Traditional research in sustainable product design strongly emphasizes the material and energy domains and aims to reduce resource consumption and waste production in the manufacturing process and at the end of the product lifecycle. Less attention has been paid to products' environmental impact in the use phase and market adoption of sustainable products, which are also important components of sustainability and are heavily influenced by how users perceive products and how they use them. This points to an opportunity to apply user-centered design strategies to the realm of design for environmental sustainability.

This thesis investigates the relationship between sustainable products and their users. The overarching goal is to gain knowledge of how to design *lovable* sustainable products, which are desirable and have strong emotional connections with users, to increase product adoption and to encourage sustainable product use. Two classes of sustainable products, residential solar photovoltaic (PV) systems and eco-feedback products, are investigated as case studies.

Residential solar PV systems produce clean energy and allow for energy independence of individual households. Via stakeholder interviews, key attributes of residential solar PV system and installation that users are concerned with are identified, including system reliability and installer reputation. Discrete choice experiments with 1773 homeowners in California and Massachusetts shed light on how they make tradeoffs between these attributes. The findings provide first-hand information on homeowners' needs and preferences for residential solar PV systems and open up opportunities for designing more attractive and more widely adopted renewable energy systems.

Eco-feedback products provide information on resource usage with the aim of encouraging resource conservation behavior in users. Surveys of 658 university students in two countries revealed that quantitative feedback in these products better aids users with higher knowledge about resource consumption; however, emotionally evocative information aids users who have low or high consumption knowledge to a similar degree. In-lab experiments with 68 participants of a wide range of ages and backgrounds show that users' resource conservation behaviors are strongly linked to negative emotions (such as guilt) towards waste of resources; and, better product evaluations have stronger links with positive emotions (such as satisfaction) towards conservation. These results suggest the value of creating emotionally evocative eco-feedback products and fostering positive emotions in order to improve user engagement.

These studies provide guidelines for sustainable product design and offer experimental approaches to facilitate future research in user-centered design for sustainability.

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Chapter 1

Introduction

1.1 Motivation

An average US citizen consumes about 13,000 kWh of electricity [1] and 420,000 gallons of water [2] a year. To save energy and water, there is significant potential in the residential sector [3], where eco-friendly consumer products can play a key role in reducing consumption and improving environmental sustainability.

Traditional research in design for sustainability strongly emphasizes the material and energy domains of producing a product [4–6]. The goals are usually to reduce resource consumption or waste production in the manufacturing process or at a product's end of life. Less attention is paid to how users perceive these products and how they use them, which could result in products' market failure or increased environmental impact in products' use phase.

Take the paper napkins in Figure 1-1 as an example, the napkin on the right is made out of 100% recycled paper and thus is more environmentally sustainable compared to the virgin-fiber napkin on the left. However, in terms of the customer review, the recycled napkin has much fewer reviews (suggesting fewer purchases) and has much lower reviewer ratings. Customers of the recycled napkins comment that even though they are happy to "be green" by purchasing this product, the napkin itself is "a little thin", "very poor quality", and feels "cheap".

Now imagine a scenario where a person is provided with such a recycled napkin. Even though one napkin should be enough to use, the person takes a handful because of the mindset that recycled paper is environmental friendly (and therefore, using them won't hurt the environment). In the end, the accumulated intensive usage would offset the environmental benefit of recycling paper, introducing the problem known as the "rebound effect" [7].

Paper napkins are not the only products that suffer from the above-described prob-

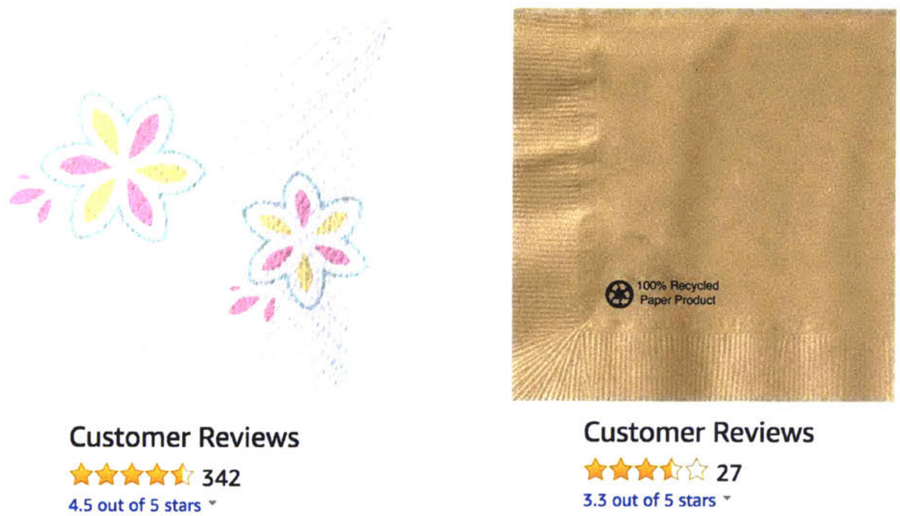


Figure 1-1: Virgin fiber paper napkin (left) vs. 100% recycled paper napkin (right)
(Image source: `https://www.amazon.com/`)

lems. Many other sustainable products, such as renewable energy systems and alternative energy vehicles, also have had limited market success. Frequently, sustainable products are perceived to be more expensive or have lower quality and thus are less desirable [8]. Even though pro-green attitudes are widespread among consumers, there exists a value-action gap that many customers who say they prefer more sustainable product choose otherwise when making purchase decisions [9]. Moreover, the way users interact with a product can strongly influence its environmental impact [10], especially for those durable consumer goods such as washing machines and television sets, which can generate up to 90% of their environmental impact during the use phase [11].

These challenges that sustainable products face motivate this following question:

How can we design lovable sustainable products, which are desirable and have strong emotional connections with users, to increase product adoption and to encourage sustainable product use?

We believe the answer lies in applying user-centered approaches to the design of sustainable products. By addressing what people need and what they want in a product, designers can facilitate consumers in making green purchasing decisions [12] as well as influence their product use [13].

Figure 1-2 presents two examples of sustainable products that achieve a balance between "green" and other properties, both of which prioritize their user experience. On the left is the Herman Miller chair. It is designed and manufactured to minimize the environmental impact (e.g. the chair can be easily disassembled at the end of life and 92% of its material is recyclable) [14]. But more importantly, it is a stylish piece of furniture that you would love to own, a comfortable chair with ergonomic shape, and a durable seat that can be used for a long time. On the right is the Nest smart thermostat. Besides being able to adjust room temperature automatically to save energy on heating and cooling, it is easy to install, intuitive to use, and fits in rooms with its sleek design.

Figure 1-2: Examples of successful sustainable product
Left: Herman Miller Setu chair (Image source: `https://store.hermanmiller.com/`)
Right: Nest Learning Thermostat (Image source: `https://nest.com/thermostats/`)

Inspired by these examples, this thesis is dedicated to investigating the relationship between sustainable products and their users. The overarching goal is to bridge the gap between the technical aspects and the social aspects of design for environmental sustainability and to demonstrate user-centered tools and methods that can facilitate the design process.

Two classes of sustainable products are investigated as case studies. One is residential solar photovoltaic (PV) system, a source of renewable energy that is usually installed at individual residences. Another one is eco-feedback design, which encourages resource conservation in users by tracking and presenting product resource usage in daily lives. The former is technology-driven while the later is consumer-facing, providing diverse examples of how user-centered methodologies can be applied to varied sustainable products. With regard to residential solar PV systems, the focus of study is on consumers' decision making on product adoption and homeowners' preferences for design features. Concerning eco-feedback designs, the focus is on understanding design factors that could influence users' perceptions of the design and their product-use behavior.

1.2 Background

This section introduces the state of the art of research on design for environmental sustainability and user-centered design. The focus is on the intersection of the two fields. Additionally, brief introductions to residential solar PV systems and eco-feedback designs are given to contextualize the studies presented in future chapters and to illustrate gaps in the literature.

1.2.1 Design for Sustainability

Three Pillars of Sustainable Products

The idea of design for sustainability originated from society's concerns about wasteful products' negative impacts on human health and natural environment [13]. Strategies such as eco-design [15] and green design [16] have been developed to reduce the environmental impacts of products, systems, and services.

Over the years, design for sustainability has been evolving and expanding its scope by including not only the environmental aspect but also the social and economic aspects of product design [17]. The social aspect considers the well-being of people, including but not limited to product users, and is reflected in a product's usability and responsible use. The economic aspect considers a product's market success and the profitability of the enterprise producing the products. These three aspects are usually known as the "three pillars of design for sustainability", sometimes described as "equity, economy, and ecology" [18], or "people, profit, and planet" as shown in figure 1-3.

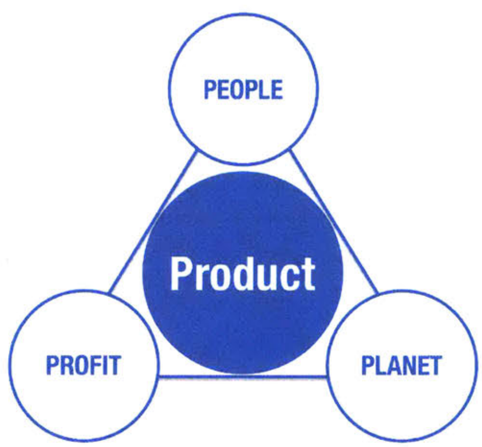


Figure 1-3: Three pillars of sustainable product
(Image source: Clark et al., Design for sustainability: current trends in sustainable product design and development [17])

The three pillars are not mutually exclusive. Instead, they support each other to achieve a product's sustainability. For example, profit allows responsible enterprises to thrive and makes it possible for them to create more sustainable products. Inversely, producing products that have a beneficial impact on the planet can also bring positive financial impact to an enterprise. Sustainable products that better serve the needs of their users are more likely to be successful in the market and therefore more profitable, and a product does not necessarily need to sacrifice its quality and style or sacrifice user well-being for environmental benefits [19]. Though the focus has long been on the environmental aspect, the triangular diagram in figure 1-3 indicates that, for any sustainable product to be successful, none of the three pillars can be missing.

A Life Cycle Perspective

A product can cast environmental impact in all stages of its life cycle, from raw material processing to the end-of-life disposal (see figure 1-4). Built upon this life cycle perspective, quantitative tools such as Life Cycle Assessment [20] were developed to evaluate the environmental impact of existing products throughout their life stages and identify opportunities for improvement. This strategy of considering the entire product life cycle is also known as the Cradle to Grave approach. The strategy has further evolved into ideas such as Cradle to Cradle [18], which proposes a high-quality use of resources to produce zero waste; and Circular Economy [21], which suggests closing the circulation loops of technical and biological resources to achieve both economic and environmental sustainability.

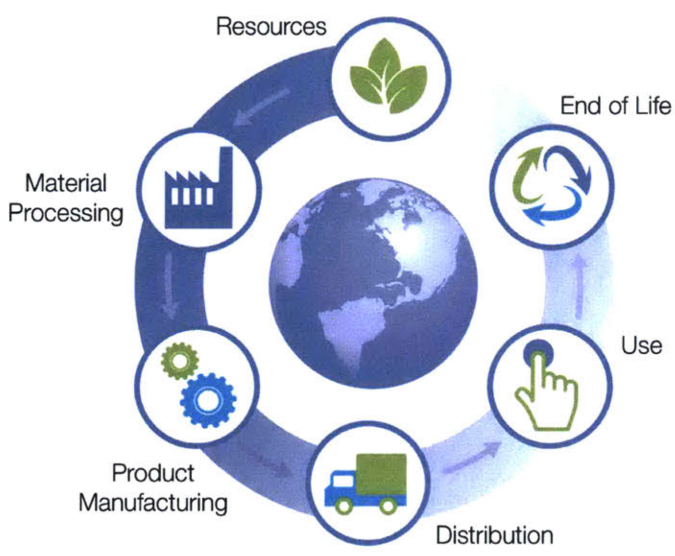


Figure 1-4: Product life cycle
(Image source: `https://www.bioprocessonline.com/`)

Designers can make a significant difference in reducing products' environmental impact by influencing the key decisions in each stage [16], for example, selecting recyclable or biodegradable materials and using renewable energy for production, minimizing material used for packaging, designing the product to last longer, and making reclaiming and reusing the product easier [22]. In the use phase where user-product interactions are the most intensive, a product's environmental impact can be minimized by influencing the use pattern or user behavior. This strategy, known as design for sustainable product use [23] or design for sustainable behavior [24], will be further discussed next.

1.2.2 Design for Sustainable Product Use

Design for sustainable product use focuses on reducing a product's environmental impact during the use phase [25–27]. It also complements traditional intervention efforts such as public campaigns [28–30] and educational programs [31, 32] to influence people's environmental attitudes, increase their environmental knowledge, and further encourage sustainable behavior.

Prevailing techniques of designing for sustainable product use fall on a spectrum from users-in-control to products-in-control [33, 34]. The typical users-in-control technique is eco-feedback [35, 36], in which users are reminded of their resource usage. Techniques on the product-in-control end, also known as smart design or intelligent design [37, 38], involve automatically taking actions to ensure behavior changes, sometimes without user knowledge or consent. Other techniques include behavior steering or behavior enabling, in which users are encouraged or guided by constraints or affordances embedded in a design [39] to behave in certain ways.

Figure 1-5 shows examples of products applying the three strategies to reduce water waste. The faucet on the left shuts off automatically every 30 seconds to prevent it being left on. The sink in the middle does not have a drain and users have to manually empty it, which takes effort and thus nudges people to be cautious about wasting. The faucet on the right tracks water usage and presents that information to users. It encourages water conservation by making the users conscious about their usage.

1.2.3 User-Centered Design

User-centered design describes design processes in which the end-users are involved and influence how a product takes shape [40]. It takes into consideration users' needs, capabilities, and ways of behaving and designs to accommodate user needs and behavior [41]. Users can be involved at varied stages of product design, including but not limited to the early stage where user needs are collected and design requirements are formed, and later

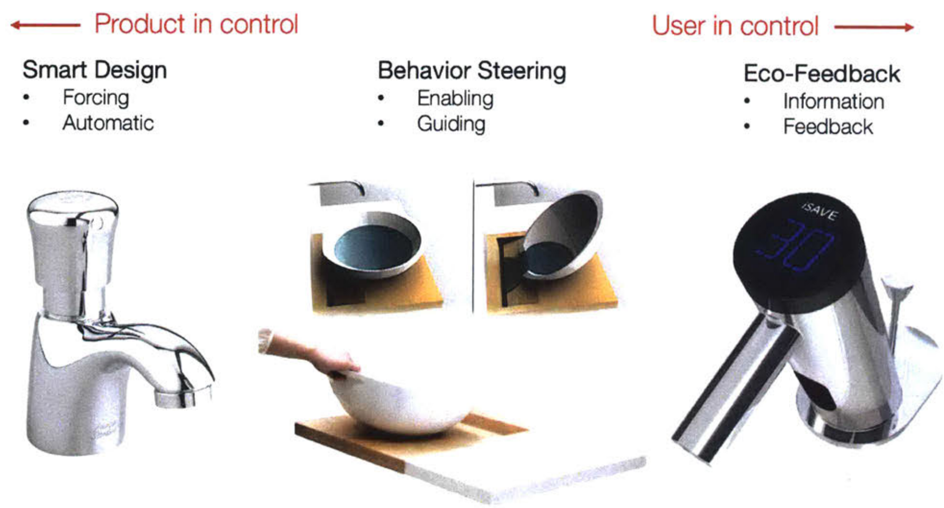


Figure 1-5: Examples of faucet/sink designs aiming to reduce water usage
Left: Pillar tap metering faucet (`https://www.americanstandard-us.com/`)
Middle: "Where's the hole" sink by Maja Ganszyniec (`http://www.yankodesign.com/`)
Right: iSave faucet, by Reamon Yu (`https://inhabitat.com/`)

stages where design concepts are tested and prototypes are evaluated [42]. Involving users in the design process leads to more effective and efficient products and contributes to the product acceptance and success [43]. For sustainable products, user-centered approaches are powerful tools that facilitate the design of more appealing products and the reduction of environmental impact in product use [10].

User Needs and Preferences

Products create value by fulfilling user needs. The quality of a product lies in the degree to which it can satisfy users' needs and meet their preferences [44, 45]. A need can be functional or emotional. It can be as basic as warmth and safety, or as high-level as esteem or self-fulfillment [46]. Understanding user needs leads to more desirable products and lowers the risk in developing new products [47].

Different users have different needs [41]. They also have different tastes and prioritize product features differently [48]. A casual photographer may choose a point-and-shoot camera for its simplicity of operation and reasonable price, while an expert photographer is more likely to pay for a pricy and complicated DSLR camera for higher quality photos. Gaining understanding of the diversity of user needs and preferences lead to a products' market success.

Prevailing techniques for identifying user needs include interviews, focus groups, and observations [47]. Designers conduct interviews and focus group studies with individuals or groups of users to discuss their needs explicitly. Observations further provide opportunities for designers to discover latent needs, which the users do not realize they have or might not be able to articulate themselves. While these methods may gain an in-depth understanding into users, they can only be applied to a small number of users at a time, constrained by both financial and human resources [40]. A survey is a convenient and economical tool to gather user needs and preferences from large number of people. Analyzing market data can provide insights into how people make actual purchase decisions [49].

With a heightened focus on the concept of sustainability over the past few decades, society and individuals have developed stronger needs to reduce our environmental footprint [50]. Sustainable products satisfy this need and in the meantime provide opportunities for individuals to advocate their environmental beliefs.

Gathering User Feedback

Eliciting feedback from users and other stakeholders on provisional design concepts can help designers understand user preferences and thus provide guidance on selecting a design direction [51]. Testing concepts with users early in the design process helps reveal issues with product usability and create opportunities to refine ideas in future iterations.

A substantial literature exists on methods for evaluating user responses to sustainable products [52], such as testing immediate user reaction via surveys [53, 54], testing short-term effectiveness of promoting sustainable behavior with in-lab experiments [54–56], and testing product usability and long-term behavior change effectiveness with field studies [10, 57]. Design representations such as rendered drawings [53], CAD models [58] and prototypes [56, 57] have been used to elicit user feedback on provisional ideas of sustainable products.

Emotional Design

Products are capable of evoking powerful emotions in users [59]: the soft glow of a bedside lamp creates a cozy feeling, a space heater comforts on a cold winter day, and solar panels on a roof provide a sense of power and pride. These user emotions provide positive experiences that foster user well-being [60] and are essential to the products' success [61].

The emotional connections between users and products are recognized as indicators and moderators for delightful product experiences [62]. Strategies and methodologies have been developed to design products to elicit intended feelings, i.e. Kansei Engineering [63], or to design pleasurable products [64]. In addition, existing research has recognized the important role emotions play in marketing [65]. Pleasant surprise and interest are both strong indicators of customer satisfaction [66]. Emotions can also impact consumers' decision making by influencing their assessment of risks associated with adopting new products or services as well as their assessment of the monetary value of goods [67].

It is recognized that one's environmental concerns and beliefs can be emotionally charged [68], and emotions such as anticipated regret or guilt are linked to consumers' decision making including the selection of sustainable products [69] and services [70], and ecological behaviors such as recycling and use of public transportation [71]. Engaging users emotionally is potentially an effective way for products to encourage sustainable behavior in users [72].

1.2.4 Residential Solar PV System

A solar photovoltaic (PV) system, often known as solar panels, converts sun power directly into electricity. It is a source of clean and renewable energy and thus can potentially play a key role in mitigating global greenhouse gas emissions. Analysis shows that the lifecycle greenhouse gas emissions from solar are considerably lower and less variable than emissions from technologies powered by fossil fuels such as natural gas and coal [73].

Residential solar systems are small scale PV systems installed in individual households. They are usually installed on roofs of residences and supply the residences with electricity on sunny days. Residential solar PV is a technology product in that it supplies residences with electricity and satisfies user needs for energy independence, lower energy bills, less environmental impact, and making a statement about their environmental beliefs [74]. In addition, the majority of residential solar PV systems are installed by professional installers rather than by homeowners themselves nowadays, making solar installation and maintenance services crucial to the user experience of adopting solar.

The adoption rate of residential solar PV system in the US market has grown exponentially in the past two decades [75] thanks to drastically decreasing prices [76] and favorable government policies [77]. Through the second quarter of 2017, accumulated residential solar installations exceeded 640,000 in California [78], equivalent to 5% of the state's households [79]. By mid-2017, 2.7% of households in Massachusetts had adopted solar [80]. In order to further market penetration of residential solar, it is vital to improving solar products and services to bridge the gap between early adopters and the early majority [81].

While many existing studies focus on improving engineering performance of solar PV systems, few have taken a user-centered design perspective or investigated the impact of solar PV system and installation service design on the diffusion of the technology. To bridge the gap, this dissertation focuses on understanding user needs and preferences for the design of residential solar PV systems and the services provided by solar installers. The overarching goal is to identify opportunities for improving the designs with the aim of accelerating the technology diffusion.

1.2.5 Eco-Feedback Design

As described in the previous section, eco-feedback is a strategy of design for sustainable product use which aims to promote pro-environmental behavior in users by making them aware of their resource consumption and its consequential environmental impact [82]. Compared to other strategies of design for sustainable product use (e.g. smart design and behavior steering), eco-feedback has the advantages of being less intrusive [55] and easier to implement [34], and has higher potential to raise users' environmental awareness [53].

In eco-feedback designs, users are in control of product usage [33]. Therefore, whether these designs effectively encourage sustainable behaviors relies on how users perceive and feel about the designs. And the way these products present resource usage information can be critical to the user perception.

Traditionally, resource usage information in eco-feedback products is presented quantitatively [83] with the expectation that rational users will behave environmentally consciously once they are made aware of the environmental consequences of their behavior. However, this assumption often fails in practice, as one study suggests that quantitative information tends to be effective only on those who already have strong pro-environmental intentions [33]. Less considered is the emotional aspect of eco-feedback designs. For example, what emotions can eco-feedback information evoke in users, and how are the emotions linked to the design effectiveness in spurring sustainable user behaviors?

To fill this gap, this dissertation applies an emotional design strategy to eco-feedback design. The goal is to gain understandings of how to design emotionally engaging eco-feedback products that are widely accepted and promote sustainable behaviors effectively in users.

1.3 Thesis Organization

There are six chapters in this dissertation. Studies of residential solar PV systems are described in Chapter 2 and 3, with Chapter 2 presenting stakeholder interviews that focused on understanding user needs, and Chapter 3 describing surveys with California and Massachusetts homeowners that measured how they made tradeoffs between attributes of solar systems and installation. Chapter 4 and 5 are dedicated to studies of eco-feedback designs. Chapter 4 reports a survey study evaluating two aspects of eco-feedback designs, the quantitative and the emotional. Chapter 5 further details an experimental study investigating users' emotional responses to eco-feedback designs. In the end, Chapter 6 concludes this dissertation with its contribution and suggests areas of future investigations.

Chapter 2

Understanding Homeowners' Experience of Adopting Residential Solar PV Systems

2.1 Motivation

A wide variety of solar panels and inverters with a range of performance, functionality and reliability are currently available in the market, providing users with options and flexibility to customize their systems. Serviceability is another important dimension of product quality [84], and a homeowner's interaction with solar installers is a critical part of the experience of adopting solar [85, 86]. This chapter and the next present interview and survey studies that were conducted to understand homeowners' experiences of adopting residential solar PV systems and to assess user needs and preferences for the systems and their installation.

As the first step to understand user needs for residential solar PV systems, semi-structured interviews were conducted with solar stakeholders. The goal is to paint a complete picture of the experience of a homeowner adopting residential solar PV systems and to gain insights into homeowners' decision making. This chapter details the process and results of the interviews.

Multiple stakeholders are involved in the residential solar PV market, all of which play important roles in the diffusion of the technology. Besides homeowners who are the end users of solar systems and make the adoption decisions, there are manufactures, who produce and supply solar equipment; government agencies, who develop policies to promote renewable energy; utility companies, who interconnect the distributed solar systems into utility grid; and installers, who configure and install solar systems for homeowners [86]. With this in mind, the interviews were conducted with not only solar owners, but also professionals in solar industry and government employees.

The interviews sought to answer the following questions:

Q1: What is the process and experience of a homeowner adopting and using residential solar PV system?

By gaining understanding of the experiences of a homeowner in selecting and engaging with a solar installer and selecting and installing a solar PV system, we could pinpoint potential barriers to solar adoption and potential directions to further improve solar products and installation services.

Q2: What attributes of solar PV systems and solar installers are the most important to homeowners?

It is well known that price, savings, payback periods, and monetary incentives are factors that homeowners consider when deciding to adopt residential solar PV systems. In this study, we aimed to identify non-economic attributes of solar PV systems and solar installers that homeowners would care about, and to evaluate what features were the most important to homeowners. We hope to identify and evaluate not only must-have or one-dimensional attributes, such as electricity production or solar panel energy efficiency; but also "delighter" attributes [87] such as a panel's visual appeal.

2.2 Related Work

2.2.1 Homeowners' Motivations for and Barriers to Solar Adoption

Numerous studies have been conducted from perspectives of behavioral economics, technology diffusion theory, and social and environmental psychology to understand the decision making of individual homeowners regarding the adoption and use of renewable energy products, including residential solar PV systems [88].

Many studies focused on investigating the motivations for and barriers to the adoption of residential solar PV. Palm and Tengvard interviewed twenty households in Sweden [89]; and Vasseur and Kemp surveyed around 800 residents in Netherland [90], to understand why they decided to install solar PV systems or why they didn't. Karakaya, Hidalgo, and Nuur interviewed 34 solar adopters and five employees of a local solar installation company in Germany; Schelly interviewed 48 solar owners in Wisconsin, US; and Sommerfeld, Buys, and Vine interviewed 22 solar owners in Queensland, Australia [91], to identify the key motivations for homeowners to install solar PV. Korcaj, Hahnel, and Spada surveyed 200 homeowners in Germany [92]; and Rai and McAndrews surveyd 365 solar adopters in Taxes, US [93], to evaluate the importance of different motivations for them to adopt solar. Rai, Reeves, and Margolis surveyd 380 solar owners in north California to understand the spark events that leads to their adoption of residential solar PV [94]. Leenheer, De Nooij, and Sheikh surveyed more than 2000 Dutch households to understand their motivations to be energy independent from utility companies [95]. Zhang, Shen, and Chan interviewed practitioners and academics to identify barriers to the diffusion of solar PV in Hong Kong, China [96]. Karakaya and Sriwannawit summarized in their review paper the most common barriers to solar PV techology diffusion in different regions around the world [97].

The revealed main motivations and reasons for homeowners to adopt solar PV systems include but are not limited to: being energy independent [89, 90, 92, 98], making financial investment and saving on electricity bills [90–93, 99], reducing impact on the environment [89–93, 95, 98, 99], demonstrating environmental awareness or setting examples for others [89, 92, 99], influenced by neighbors and/or peers [92–94], receiving information from installers [91, 94, 98], interested in the technology itself [93–95], and supporting local economy [92]. Similarly, barriers to solar adoptions have been identified, including high cost and long payback period [89, 90, 96, 97], space and location constraints [89, 96], objections from neighbors [89], lack of policy and governmental supports [96, 97], and difficulty of seeking information [94]. In addition, it has been pointed out that these motivations and barriers vary across context, such as local economy, climate, and market maturity [97].

2.2.2 Residential Solar PV System as A Product

Attributes of a solar PV system that influence market success have been investigated on three different levels: perceptual, design, and technical, from the general to the specific. Perceptual level attributes are concerned with how a product is regarded by consumers. Perceptions of the same product can easily vary across individuals and thus perceptual level attributes tend to be subjective. Technical level attributes are concerned with the technical specifications of a product. While technical attributes are frequently evaluated from technology development perspective, they may not be familiar to the product end-users. The design level, which bridges the previous two, considers attributes of a product that are both objective and tangible and can be easily understood by the end-users.

The most frequently considered perceptual level attributes of an innovative product are its *relative advantage, perceived risk, complexity, compatibility, trialability,* and *observability* [100, 101]. Vasseur and Kemp surveyed solar adopters and non-adopters in the Netherlands and found that the perceived affordability, environmental benefits, and ease of installation were key predictors for solar adoption [90]. Similarly, Zhai and Williams surveyed home-owners in Arizona, US, and found that compared to non-adopters, solar adopters perceived solar PV to be significantly more environmentally friendly, significantly less expensive, and require significantly less effort to maintain [102]. They also found that non-adopters considered cost to be a more important factor in their purchase decisions, while adopters considered environmental benefit and ease of maintenance to be more important. Claudy, Michelsen, and O'Driscoll compared Irish homeowners' perception of four microgeneration technologies, including micro wind turbines, wood pellet boilers, solar PV, and solar water heaters [103]. They found that solar PV was perceived to have the highest environmental benefit among the four. However, the perceived environmental benefit of solar PV had no significant influence on homeowners' willingness to pay. Instead, perceived independence from traditional sources of fuel was a strong predictor of homeowners' willingness to pay for solar PV.

Key technical attributes of a solar PV system include its efficiency [104, 105], reliability [106] and durability [107, 108], all of which are directly related to the system's energy production. Chen, Honda and Yang extracted technical specifications of solar panels from manufacturer data sheets and applied machine learning algorithms to solar PV market data in California, US, to identify the key attributes that influence the product's market success [85]. The attributes explored included a solar panel's weight, size, power output, certifications, and cost, among others. They found that power warranty, efficiency at standard testing conditions, and time on the market were the three most critical attributes that influenced the product's market share. Frischknecht and Whitefoot assessed the revenue potential of four PV materials (monocrystalline silicon, polycrystalline silicon, tandem-junction amorphous silicon, and copper indium diselenide) by incorporating attributes such as temperature sensitivity, voltage, and current output, etc. of each type of solar PV into an engineering performance model [109]. They found that increasing power output of solar panels (by either increasing their voltage or current) could open new market of small roof-size population.

To investigate user preferences for solar PV systems, design level attributes that can be easily understood by end-users need to be identified. In Frischknecht and Whitefoot's work [109], attributes including system capacity, roof space, production warranty, payback time and net purchase price were presented to Australian homeowners in a survey to evaluate their preferences for solar PV systems. Scarpa and Willis studied British households' willingness to pay for micro-generation systems including solar PV, solar thermal and wind turbine, with considerations of the system capital cost, energy bill savings, maintenance cost, contract length, and inconvenience of installing systems [110]. Islam and Meade looked into Canadian homeowners' preferences for solar PV regarding its initial investment, energy cost savings, CO_2 emission savings, payback period, and so on [111]. Bao, Honda, Ferik, Shaukat and Yang investigated US residents' preferences for solar panels' visual appearance while also considering their reliability, efficiency, unit price, and whether the system can be tied to the grid [112].

2.2.3 Research Gap

While many existing studies investigated homeowners' motivations for and barriers to solar adoption, and many other studies focus on the perceptual level or technical level attributes of a solar PV system, few have taken a user's perspective or investigated the impact of solar PV system design on the diffusion of the technology.

In addition, solar installation and maintenance services provided by installers are crucial to the user experience of adopting solar. This is especially true when third-party PV ownership [113] became popular and solutions that simplify the solar installation process such as plug-and-play PV systems [114, 115] become available. Factors that can influence users' adoption experience such as information channels [116] and buy-versus-lease options [117] have been explored. However, studies in this area are still sparse.

To bridge these gaps, this chapter focuses on understanding homeowners' experience of adopting residential solar PV systems and assessing user needs for residential solar PV systems and installation services.

2.3 Methods

2.3.1 Participant Recruitment

This study involved interviews with eighteen individual stakeholders of residential solar PV in the New England region of the United States (mainly in the state of Massachusetts). The interviews were conducted in June and July 2015. Participants were recruited via email and a snowball sampling method was used, where participants were asked to recommend other potential participants.

It was intended that diverse solar stakeholders were recruited to provide different perspective and point of view. The participants included both homeowners who had adopted and had not yet adopted solar, professionals in solar industry, and government employees working in renewable energy sector. Detailed information about the participants is summarized below.

Homeowners:

- Seven solar owners lived in Massachusetts
- Two homeowners who were interested in residential solar but hadn't adopted yet (one lived in Massachusetts, one in Connecticut)

Industry Professionals:

- One sales manager at a local solar installation company
- Two energy consultants
- Four solar "coaches" who voluntarily organized Solarize Mass program [118]

Government Employees:

- One manager at a Massachusetts public agency to advance clean energy
- One municipal representative

2.3.2 Interview Procedure

Twelve interviews were conducted in person at locations that were convenient to the participants, among which three solar owners were interviewed at their residences where their solar systems were installed. The other six interviews were conducted via phone.

The interviews were semi-structured and consisted of open-ended questions. For solar owners, the interviews focused on their adoption decision and their experience as users of solar PV systems. For homeowners who hadn't adopted solar, the interviews focused on what they knew about solar and the reasons why they hadn't adopted yet. For industry professionals, their observations on homeowners' solar adoption decision were asked. For the solar installer, the interview also covered their selection of solar equipment, strategy of recruiting customer, and process of designing and installing solar systems for their clients. For government employees, the interviews focused on the policies they implemented to increase residential solar adoption. The interview outlines are presented in Appendix A.

Each interview took about an hour. Audios were recorded and notes were taken during the interviews. Results are summarized by theme and presented below.

2.4 Results and Discussion

2.4.1 Homeowners' Solar Adoption Decision Making

The general process of a homeowner's decision making regarding adopting solar PV system is summarized in Figure 2-1. Only homeowners who had their systems installed by professional installers, which was the common case among all adopters, were considered here. Homeowners who installed their solar panels by themselves were not considered in this study.

A homeowner become interested in installing solar PV system for variety of reasons, including being exposed to solar commercials on TV, in newspaper, by mail, online, and so forth; or being recommended by friends, relatives, or neighbors. Once they are interested in installing solar, they may reach out to solar installers or respond to solar installers who

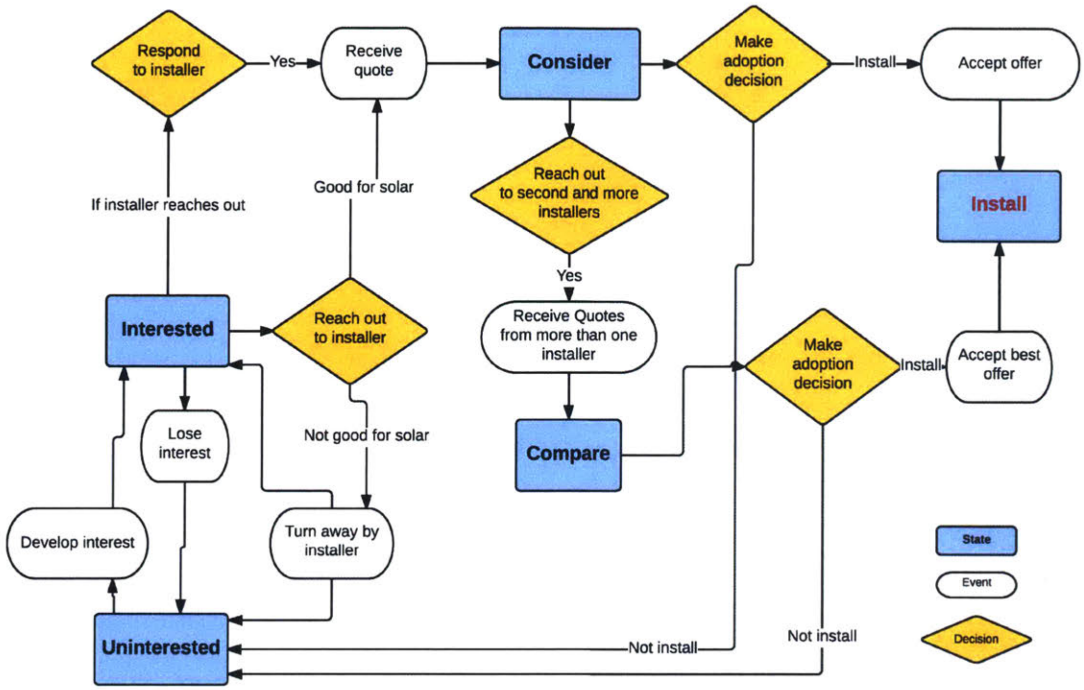


Figure 2-1: Flow chart of homeowners solar adoption decision making

have contacted them. An installer will usually schedule an on-site visit with the homeowner to evaluate the orientation, quality, and surroundings of the residence's roofs to determine if they are appropriate for rooftop solar installation. Some installers will use satellite view of Google Maps to conduct this evaluation off-site. Unfortunately, some homeowners will be rejected by installers at this point because their roofs are either too old, have wrong orientation (south-facing roofs are the optimal; some east and west facing roofs can also do; but north-facing roofs are considered inappropriate for installing solar), or have trees shading them. Sometimes installers will also suggest homeowners to replace their roofs before installing solar.

Once determining that a residence is appropriate for solar installation, an installer will provide homeowner with a preliminary quote, which usually consists of the capacity of solar system, the layout of solar panels on roof, the overall cost, the payment method, and the projected savings on electricity bill over the lifespan of the system. If the homeowner decides to install solar and is satisfied with the quote, they will accept it and sign contract with the installer. But it is not unusual that the homeowner will request for changes of the system design, such as to increase system capacity, to use different equipment, or to change panel layout. The installer will then iterate on the quote until it satisfies the client's need.

Some homeowners will contact multiple installers and compare the quotes provided by them. If a homeowner decide to install solar, they will choose to work with the installer who provides the best offer. Among the seven solar owners we interviewed, five explicitly said or indicated that they contacted multiple installers; and at least two of them received quotes from more than one installer.

Installers usually decide the capacity of solar systems based on residences' utility bill history. One installer usually provides more than one type of solar panels and inverters. A common strategy is to provide solar panels in different quality tiers and to give customers the flexibility to choose the ones that best suit their needs.

A homeowner can purchase and own a solar system. Alternatively, a homeowner can lease a system or install a system with power purchase agreement (PPA). In the former case, the homeowner will pay all the cost upfront either out-of-pocket or with loans. In the latter case, they will pay monthly rent for the system or pay for the electricity generated for a time span, which is usually 20 years. Among the solar owners interviewed in this study, five purchased and owned their systems and the other two leased. Those who purchased appeared to have more autonomy on the design of the systems and the choice of equipment, while those who leased would let their installers make decisions regarding the system design. Also, those who purchased appeared to have more choices of solar installers, while those who leased could only work with large installer companies that were financially sound enough to provide the leasing option.

2.4.2 Motivations for and Barriers to Homeowners' Adoption of Solar PV

The main motivations for a homeowner to adopt solar PV were summarized from the interviews and are presented below in categories:

- **Economical**: to save on electricity bill; to prepare for future increase in electricity price; to receive special discount or government rebates
- **Environmental**: to reduce carbon footprint and pollution by using renewable energy
- **Social**: to serve as role models for children by using renewable energy; to raise environmental awareness in the neighborhood; be influenced and convinced by friends/relatives/neighbors to adopt; to participate in the community-based campaign
- **Others**: to be energy independent; interested in the technology

Among the seven solar owners interviewed, five indicated that environmental motivations were the main reasons that they installed solar. They expressed concerns over global warming, air pollution, etc. and expressed willingness to make effort to contribute to the environmental sustainability. Among them, one solar owner said he would adopt solar "as long as it's affordable", while the others did the calculation and decided installing solar would also make economic sense. Only one solar owner we interviewed indicated that "to save money" was the main motivation for him to adopt solar. One solar owner didn't explicitly indicate what was the main motivation for him to adopt solar; instead, he expressed a strong interest in the technology itself. He was excited talking about the design details of the system and said he was actively tracking the energy production of his system.

The barriers for homeowners to adopt solar were summarized from the conversations with non-adopters as well as with the solar industry professionals. They are presented below in four main categories:

- **Economical**: not having enough cash to purchase; not having enough credit to lease; electricity bills are low thus will not benefit much from installing solar
- **Roof and house condition**: roof is too old; roof doesn't have enough space; roof doesn't have solar favorable orientation; roof shaded by trees; buildings locate in historical regions and need special permit for installing solar
- **Risk and uncertainty**: the price of solar might go down and better products might become available in near future; policies might become unfavorable for solar users (net-metering might be cancelled or adjusted by local utility)
- **Others**: solar panels are not aesthetically appealing; the purchasing and installation process is too complicated; don't have sufficient understanding about this technology; expecting to move out of the residence soon and thus don't want to commit to large renovation projects such as installing solar PV systems

These identified motivations and barriers were consistent with the literature.

2.4.3 Solar Installation Process

From the interviews we learnt that, the actually solar installation (including mounting solar panels on roof, installing inverters, connecting wires, etc.) usually takes no more than a few days. However, the time from a homeowner signing contract with an installer to the solar system being in use can take up to a few months. Figure 2-2 summarizes the timeline of a solar installation project.

Permits including building permit and electrical permit need to be applied from municipal departments before installing solar, and installers usually take care of these applications. After installation, building and electrical inspections will be conducted. Once inspections are passed, the installers will contact the utility and secure the interconnection of the PV system with the grid. The detailed permitting process varies from city to city and the interconnection application varies across utility companies.

Figure 2-2: Solar system installation timeline

2.4.4 Solar System In Use

Solar owners interviewed in this study benefited from net metering program. This means solar energy generated and immediately used onsite will not result in any charges; and when the solar systems produce more electricity than the households consumed, the extra electricity will be sent back to the grid and be credited. The solar owners are only billed for their "net" energy consumption on monthly bases. If the net energy consumption is negative in any months, credits will be received and can be applied to future electricity bills. Most of the solar owners we interviewed had zero electricity bills in summer months when the solar production peaked, and received significantly reduced electricity bills even in winter months. Solar owners who purchased and owned their systems were able to apply federal tax rebate for their solar systems. They were also eligible to earn Solar Renewable Energy Certificates (SRECs), which can be sold to gain extra money in addition to savings on electricity bill. There are SREC brokers who manage the trading of SRECs for solar owners. The net metering and SREC policies also vary from region to region.

Overall, the maintenance effort for the solar systems is minimal. In northeastern America, where rain and snow is abundant, the systems need no regularly cleaning. In addition, snow usually slides down easily from the panels because the panels are usually tilted. However, the solar owners we interviewed reported some unexpected breaking downs of the systems, including squirrels building nests under solar panels and chewing wires. For the two solar owners we interviewed who leased their systems, the solar installers took care of all repairments when the system broke down. For those who purchased and owned the systems, their installers also took care of the repairments if they were covered by warranties. However, for one interviewer who adopted solar in year 2006, his solar installer went bankruptcy and the original warranty became invalid. Therefore, he needed to find another contractor to repair his system when it broke down.

Two solar owners we interviewed mentioned that they were able to track the production of their systems online or with mobile application, and they did that regularly to check if their systems were performing normally. All solar owners we interviewed except one didn't report any changes of electricity usage behavior after adopting solar. One solar owner reported to shift energy intensive activities, such as using washing machine and drier, from nights to days so that he could use more energy that was produced by himself, even though he recognized that the electricity bill would not be any different (because of net metering).

2.4.5 Community-Based Solar Campaign

From the interviews we noticed a phenomenon that drastically changed the homeowners' adoption decision making, which was the community-based solar campaign. The Massachusetts Clean Energy Center initiated the Solarize Mass program, which looked to increase the adoption of residential solar PV systems through a grassroots educational campaign, starting from year 2011. Each participating community (usually in unit of city or town) had local volunteers to organize the campaign. They would select one or a few designated solar installation companies to work with. Homeowners in the community would receive free roof assessments. Once enough homeowners opted in the program, the installer(s) would provide a group discount. Other community-based solar campaigns existed besides the Solarize Mass program.

Such campaigns appeared to be successful. Homeowners benefited from the lower price of installing solar; installers profited from increased clients; and overall, the program largely increased the solar adoption. The number of small-scale solar electricity projects in almost every community doubled as a result of the Solarize Mass program [118]. Actually, one of the solar owner interviewed in this study adopted solar via the community-based campaign. And another solar owner organized such campaign in her own community one year after the interview.

Community-based solar campaigns significantly change homeowners' adoption decision making. Via the campaigns, homeowners have easy access to credible and transparent information about the benefits of residential PV [119]. Researching and comparing installers is no more necessary and thus the decision making is much more straightforward. Also peer effect becomes salient: on one hand, homeowners feel less risky about adopting solar when they see many other people around them doing so; on the other hand, there is a sense of contributing to the community as the installers usually offer higher discount when more homeowners participating in the program.

2.4.6 Key Features of Solar PV System and Solar Installing Services

Key features of solar PV systems that homeowners consider when making solar adoption decisions were summarized from the interviews. They are:

- **Panel efficiency**: efficiency of a solar panel is the percentage of sunlight power it converts to electricity. To produce the same amount of electricity, fewer high-efficiency panels are needed compared to low-efficiency panels. Thus homeowners with limited roof space usually choose higher efficiency panels to achieve larger system capacity.

- **Panel degradation rate**: solar panels' efficiency will go down over time as solar cells degrade. Therefore, even solar panels are usually sold with 20 to 30 years lifespan guarantees, a 20 year old solar system does not produce as much power as it was new. All other things being equal, solar panels with lower degradation rate will produce more energy over the lifespan compared to panels with higher degradation rate. Manufacturers usually provide production warranties to guarantee that their panels will retain a certain percentage of their production capacity overtime.
- **Panel reliability**: solar panels may break soon after installation due to manufacturing defects, or they can break during use as the system exposed to heat, cold, and humid. Panels are usually tested under standard testing conditions and those passing the tests will be granted with certifications. Manufactures also provide equipment warranties for their panels to guarantee that they will be free from problems.
- **Panel manufacturer**: some solar manufacturers are based in US but many more are international. Some homeowners choose panels produced by local manufacturers over those provided by foreign manufacturers to support local economy and to reduce carbon footprint created by importing panels overseas.
- **Inverter**: inverters convert DC electricity produced by solar panels into AC electricity, which can be used directly by household appliances. There are three major types of inverters: central inverters (also known as string inverters), micro-inverters, and power optimizers. Central inverters are the most cost-effective. One central inverter connects to an array of panels. If one solar panel in the array break or is shaded by a tree, the central inverter will prevent all other panels from working. Micro-inverters, on the contrary, will allow the other panels to continue operating at full power since each panel has its own micro-inverter. Power optimizers are compromise between central and micro-inverters. For power optimizer, one inverter connects an array of panels but each panel has its own power optimizer. If one panel in the array fails, power optimizer will allow the other panels to keep working but with slightly lower efficiency.
- **Environmental benefit**: solar PV systems create zero carbon dioxide (CO_2) emission or pollution while in use. From a life cycle perspective, solar PV still provides significant environmental benefits compared to generating electricity with fossil fuel [120]. Solar installers often include such environmental benefit of solar systems in design proposals and present the environmental benefits in forms of equivalent CO_2 reduction, equivalent trees planted, or equivalent mileage of vehicles whose greenhouse

gas emissions are offset.

- **Aesthetics**: the solar panel appearance appears to be an important factor that influences the solar adoption decision, consistent with our previous finding [112]. The municipal representative that we interviewed, who worked for a Massachusetts town with a historic district, explicitly pointed out that many homeowners purchased residences in the town because the houses looked beautiful and had a historical appearance. Thus they would not want the modern and industrial looking solar panels to interfere with that.
- **Energy storage**: a few solar owners expressed interests in installing energy storage systems, such as battery energy storage, in companion with their solar PV system to gain independence from the utility companies. Without energy storage, solar systems tied to the utility grid are shut down for safety concerns when there are power outages. With energy storage, however, solar owners can keep generating and consuming energy even when the grid goes down. Nevertheless, affordable energy storage solutions were not immediately available at the time of the interviews.

There are also many factors about solar installers that have impact on homeowners' decision making on adopting solar.

- **Equipment choices**: there are hundreds of brands and models of solar panels exist on the market, if not any more. However, one solar installer provides at most a handful of choices. Different installers have different strategies of selecting equipment. Some are more willing to provide equipment that is new to the market, which usually has more advanced features, but is more risky in the sense that its reliability hasn't been proved by the test of time; the other installers, on the contrary, tend to provide equipment that has been on the market longer to minimize the risks. Some installers provide premium panels, which have higher performance and tend to be more expensive; the other installers choose to provide economy panels, which sacrifice some performance and quality for higher affordability. Homeowners who have specific requirements for the brand or performance of equipment will use this as a selection criterion for solar installers.
- **Flexibility with system design**: sometimes, homeowners have very specific requirements for the system design and they will prefer solar installers who can flexibly adjust the design according to their needs. One solar owner we interviewed told us that, he wished the solar system to have an "as large as possible" capacity. Unfortunately, the roof size of his house was limited and most of the installers he talked to designed relatively small systems for him. However, one installer creatively designed

a large capacity system with an extension structure on his garage roof. The solar owner finally chose to work with this installer.

- **Workmanship warranty**: many solar installers provide warranties on their workmanship to protect their customers from installation-related defects. This type of guarantee states that the design, assembly, and installation of the solar systems are all done correctly, and any defects that may arise will be fixed free of charge.
- **Financing option**: as described earlier, there are two major type of financing options for adopting solar: purchasing and leasing/PPA. While all solar installers offer the purchasing option, only a few offer leasing or PPA option.
- **Local/National**: local companies are usually more familiar with the local market. They know better of the regional policies, permit application processes, etc., and are more likely to have experience with designing and installing systems for the local climate and environment. However, they are usually smaller on scale compared to national companies, and therefore are less likely to provide leasing options and might not be as financially stable as national companies. Besides these considerations, homeowners may choose local companies over national companies as an effort to support local economy and to create local jobs. This was especially salient in the installer selection of community-based solar campaigns.
- **Reputation**: the reputation of a solar installation company is reflected in ways including reviews on websites such as SolarReviews and Yelp, word-of-mouth among homeowners, etc. The solar owner who adopted solar in year 2006, which was the earliest among all solar owners that we interviewed, found his solar installer in yellow pages. These days, more homeowners research solar installers via Internet. Additionally, many homeowners choose solar installers that their friends, neighbors or relatives recommended.

Besides all the above factors, the overall cost of installing solar and savings on electricity bills are two key aspects that all solar owners consider. A common metric for solar panel cost comparison is dollar-per-Watt, which could be calculated by the total cost of a solar system over its capacity. In a solar system design proposal, installers will provide detailed cost breakdown of the system, and factor in the federal tax rebate and/or local governmental incentives as well as an estimated value of SRECs. In addition, the design proposal will include a prediction on electricity production of the system, the estimated average monthly savings on electricity bills, and the accumulated savings over the system's lifetime. Based on the cost and estimated savings, metrics such as payback period and rate of return are calculated to help homeowners further evaluate the value of the investment. There are many uncertainties in these calculations. For example, the value of SRECs fluctuates, and the savings on electricity bills largely depend on the electricity price. Because of these, one solar owner we interviewed made her own spreadsheet to calculate the cost and savings of solar systems within different scenarios.

2.5 Conclusion

This chapter summarizes the interviews with stakeholders of residential solar PV systems, including homeowners, industry professionals, and government employees. The general experience of a homeowner adopting solar PV system is outlined. Homeowners' main motivations for and barriers to solar adoptions are summarized. Key factors that homeowners considered when making decisions on solar adoption are identified.

Previous study has discovered that decision making regarding PV panel choice in the adoption of residential solar PV system is made predominantly by PV installers [85]. Our interviews further reveal that solar installers are intensively involved throughout the entire process of a homeowner adopting solar PV system, and therefore is a key element of the customer experience of adopting residential solar PV systems.

Eight key features of solar systems that homeowners consider most often when adopting residential solar PV systems are identified. They are: panel efficiency, panel degradation rate, panel reliability, panel manufacturer, inverter, environmental benefits, aesthetics, and energy storage. Six key features of solar installers are identified. They are: equipment choices, flexibility of system design, workmanship warranty, financing option, local or national, and reputation. Other factors that homeowners take into considerations are cost and savings, and time and complexity of solar installation.

The next chapter will present a survey study based on these interview findings. The survey was conducted with homeowners in California and Massachusetts, and focused on assessing homeowners' preferences for different factors of solar systems and solar installing processes.

Chapter 3

Assessing Homeowner Needs and Preferences for Residential Solar PV and Installation

3.1 Motivation

In the last chapter, key features of solar PV systems and solar installation services were identified via stakeholder interviews. In this chapter, we further investigate how homeowners prioritize these attributes.

A survey was designed and deployed to solar adopters and non-adopters in two US states, California and Massachusetts. These two states were chosen as one representing a more mature solar market (California) and another representing a market that is less mature (Massachusetts).

Discrete choice experiments were conducted to understand homeowners' preferences for features of solar PV system and solar installers. In addition, we are aware that not all users have the same preferences, and thus consider the preference heterogeneity among homeowners.

The following research questions are posed:

Q1: How do homeowners make tradeoffs between different attributes of solar PV systems and solar installers?

When selecting products with multiple features, users often need to make tradeoffs between multiple attributes. For solar PV systems, homeowners would need to make tradeoffs between installation price, long term saving, system performance, and so on. Understanding these tradeoffs can help solar manufacturers and installers to informedly prioritize their product features and services.

Q2: How do preferences for solar PV systems and solar installers compare across homeowner demographics?

We expected homeowners in California and Massachusetts to have distinct preferences for solar PV systems because of the dissimilar solar irradiation levels and PV market maturity levels between the two states [86]. Similarly, we anticipated different preferences between solar adopters and non-adopters under the assumption that they would have different familiarity with solar PV systems, and different perceptions of the technology [102]. In addition, we expected age and income of the homeowners to influence their preferences. Previous studies have found that older households were less inclined to adopt micro-generation technologies [121] and adopters tend to have higher income and higher environmental awareness [122]. Identification of these preference heterogeneities among populations will help to guide the design of products and services for various market segments.

3.2 Related Work

3.2.1 Evaluating Preferences for Renewable Energy Products with Discrete Choice Experiment

Discrete choice experiments have been widely used to study consumer preferences for renewable energy products. Bergmann, Hanley and Wright [123] and Ku and Yoo [124] studied the willingness-to-pay for the generic renewable energy in Scotland and Korea, respectively. Van Rijnsoever, Van Mossel and Broecks [125] and Borchers, Duke and Parsons [126] studied the public perception and acceptance of different energy technology, including PV solar, wind, biomass, coal, nuclear, and natural gas. Scarpa and Willis [110] studied the British households' willingness to pay for micro-generation systems such as PV solar, solar thermal and wind turbine. Kaenzig, Heinzle and Wustenhagen [127] evaluated consumer preferences for electricity products with different proportion of renewable energy in Germany. Islam and Meade [111] investigated the impact of attribute preferences for residential solar PV systems on the adoption timing. Ladenburg and Dubgaard [128] and Bao, Honda, Ferik, Shaukat and Yang [112] investigated the visual appearance of offshore wind farms and solar panels, respectively, and their impact on people's willingness-to-pay and preferences.

The following two characteristics of these previous discrete choice experiments were observed. First, a majority of these studies treat renewable energy as a mere substitute for a traditional source of electricity with added environmental benefits [123–125]. Some studies also view renewable energy as part of the energy mixed provided by utility companies [126, 127]. Consequently, these choice experiments focused on investigating the general public's acceptance of renewable energy and evaluated perceptual level attributes such as the impact on landscape and wildlife, reduction on air pollution, energy safety and supply security. Second, there was a strong emphasis on economic factors such as capital cost, maintenance cost, energy bill, payback period, and tax incentives for renewable energy. Some studies even included multiple of these economic factors into one single choice experiment [110, 111]. Only a few choice experiment studies treated renewable energy as technology products and included design level attributes [110–112].

3.2.2 Comparing Preferences for Renewable Energy Products across Homeowner Demographics

The links between homeowners' socio-demographic factors and their willingness to adopt solar PV or use renewable energy have also been explored in previous studies. Mozumder, Vsquez, and Marathe conducted a survey with residents in New Mexico, US, and found that their environmental concerns, income, and household size were positively related to their willingness to pay for renewable energy [129]. Sardianou and Genoudi conducted a survey with Greek consumers and found that middle aged and highly educated people were more likely to adopt renewable energies [130]. Willis, Scarpa, Gilroy and Hamza surveyed British households and found households with members older than 65 years of age were much less likely to adopt renewable energy products, including solar PV, solar thermal and wind turbines [121]. Additionally, local environmental such as level of solar radiation [131], social factors such as cost of electricity [131] or fossil fuel [111], political factors such as governmental financial incentives [111, 131], and peer effect, such as being recommended by friends and professionals [110] or high solar adoption rate in the neighborhood [111, 132], have been found to be important factors influencing the adoption of residential solar PV.

This study considers multiple socio-demographics of homeowners, including their age, income, state of residence, as well as their solar ownership. Comparing preferences across demographics could help to guide the design of products and services for various market segments. Comparing between solar adopters and non-adopters could further pinpoint potential barriers to solar adoption.

3.3 Methods

A survey was designed to evaluate homeowners' preferences for residential solar PV systems and installation services on a large scale. A thorough process was taken to design the survey, especially the discrete choice experiments [133]. Multiple rounds of pilot studies were conducted, first with five homeowners to shape the questions and the wording; then with 36 respondents recruited on Amazon Mechanical Turk, a human intelligent crowdsourcing platform, for reading level and timing; and in the end with 120 respondents recruited via Peanut Labs, an online market research company, to test the data analytic methods. Modifications to the survey were applied based on the feedback of each round of pilot testing.

All participants were asked demographic information including the state they reside in, their gender and age, along with their household yearly income.

3.3.1 Discrete Choice Experiment Attributes and Levels

The survey included two discrete choice experiments, one for solar installers and the other for solar systems, assuming adopters would first choose an installer to work with and then choose a solar system to install among options that the installer would provide. Only a subset of the attributes identified in the interviews was included in the discrete choice experiments. The number of attributes was limited to six per choice experiment to keep the survey manageable for respondents. The importance of these factors to the solar adoption decision making and the respondents' familiarity with these attributes were taken into consideration in the selection process. Price was not included as attribute because the price of installing a solar system depends on the system size, which can vary drastically according to a household's energy demands. Instead, percentage savings in electricity over 25 years was used to represent the financial factors of installing solar.

The attributes and levels are summarized in Table 3.1. These levels of the attributes were selected to represent the current solar markets and the potential markets in the near future. Detailed introductions to the choice experiment attributes and levels were provided to the respondents in ways that homeowners who had little knowledge about residential solar PV systems could easily understand. Illustrations were provided to help explain some of the attributes. These were to make sure all respondents, regardless of their previous experience with the residential solar, would have the same basic understanding of the attributes to make informed responses to the discrete choice questions. Introductions to the attributes (as were shown to the survey participants) are summarized in Appendix B.

Each discrete choice question presented three options of solar installers or systems with random combinations of attribute levels. In addition, a "None" option was provided in each question, allowing the respondents to choose none of the three options. Prohibition rules were set to avoid dominant bundles of attributes (e.g. the best functionalities and the highest savings were prohibited to appear together in any solar system options). Each discrete choice experiment included sixteen questions. Sawtooth Software was used to design the questionnaires. Figure 3-1 provides two examples of the discrete choice questions.

At the beginning of the discrete choice experiments, the respondents were asked to imagine shopping for solar systems (see Appendix B). For those who had already installed

Table 3.1: Attributes and levels of the discrete choice experiments

Attribute	Levels
Discrete Choice Experiment about the Installers	
Attribute	**Levels**
Independent reviewer rating	Average (3 stars), Good (4 stars), Excellent (5 stars)
Installer-customer collaboration	Independent, Moderately collaborative, Collaborative
Equipment technology	Cutting-Edge, Standard, Traditional
Total project time	1/2 Month, 1 Month, 2 Months, 4 Months
Warranty	5 Years, 15 Years, 25 Years
Savings in 25 years	10%, 25%, 40%, 55%, 70%
Discrete Choice Experiment about the Systems	
Attribute	**Levels**
Panel efficiency	15.5%, 18.0%, 20.5%, 23.0%, 25.5%
Panel visibility on roof	High, Low
Inverter type	Central inverter, Micro-inverter, Power optimizer
Failures in first five years	0 Failures, 1 Failure, 2 Failures, 5 Failures
Environmental benefits (reduced CO_2 emission equivalent)	3 Acres of forest, 6 Acres of forest, 9 Acres of forest
Savings in 25 years	10%, 25%, 40%, 55%, 70%

solar panels, they were asked to imagine this was their first time shopping for solar. The scenario asked the respondents to imagine that they had just bought and renovated a house, and decided to invest some extra budget into solar panels to save money on electricity in the long run. The intention of the scenario was to encourage respondents to express preferences as if they were making decisions in the real world. In addition, the scenario exempted the respondents from concerns such as old roofs or limited budget to discourage them from always choosing "None" even if they could not adopt solar in the real world for these reasons.

3.3.2 Data Collection and Quality Control

The survey was active between late April to early October 2017 and was distributed via three channels. Peanut Labs, an online market research company, was used to collect responses from homeowners in California and Massachusetts. Qualtrics, another online market research company, was used to collect responses from solar owners in the two states. Besides, connections to local solar owner communities and solar installers were used to collect responses from more solar owners. Screening questions at the beginning of the survey allowed only homeowners residing in California or Massachusetts to proceed. Additional screening questions were ask to decide if a homeowner had adopted solar or not.

Much effort was spent to ensure the quality of collected data. Prompts in the survey

Below are three installers that are available in your area. Please indicate the one you prefer the most. You can choose NONE if you don't prefer any of them. If more than one option is acceptable and you don't have a strong preference for one over the others, you can choose any of them.

(1 of 16)

	Installer 1	Installer 2	Installer 3	NONE
Independent Review Rating	Average ★★★☆☆	Good ★★★★☆	Good ★★★★☆	I wouldn't choose any of these.
Installer-customer Interaction	Collaborative	Collaborative	Moderately Independent	
Equipment Technology	Standard technology	Traditional technology	Cutting-edge technology	
Total Project Time	2-month project time	1/2-month project time	4-month project time	
Warranty	15-year warranty	25-year warranty	5-year warranty	
Saving in 25 Years	25% savings	10% savings	25% savings	
	○	○	○	○

If you have any questions about the solar installer features, click here to review the definitions.

Below are three systems that the installer proposes. Please indicate the one you prefer the most. You can choose NONE if you don't prefer any of them. If more than one option is acceptable and you don't have a strong preference for one over the others, you can choose any of them.

(1 of 16)

	System 1	System 2	System 3	NONE
Panel Efficiency	15.5% efficiency	23% efficiency	25.5% efficiency	I wouldn't choose any of these.
Panel Visibility	High visibility	Low visibility	Low visibility	
Inverter Type	Power optimizer	Micro-inverter	Central inverter	
Failure in First Five Years	3 failures	0 failures	3 failures	
Environmental Benefits	3 acres of forest	3 acres of forest	6 acres of forest	
Savings in 25 Years	70% savings	55% savings	40% savings	
	○	○	○	○

If you have any questions about the solar system features, click here to review the definitions.

Figure 3-1: Example discrete choice questions of installers (above) and systems (below)

reminded respondents to read the materials and questions carefully. Time limits prevented respondents from clicking through the introduction pages too quickly. Control questions were used to screen the responses. Responses that satisfied all below criteria were kept for further analysis [134, 135]:

- **Passing all control questions.** Two multiple-choice questions that explicitly instructed respondents to select a specific option were embedded in the middle and near the end of the survey. Responses that weren't the specified options were considered failing the control questions.

- **Providing meaningful responses.** For the open-ended questions that asked the respondents to write in textboxes, gibberish text entries (such as a random sequence of letters) were excluded.
- **Consistent demographic information.** For responses collect via Peanut Labs and Qualtrics, the age of the respondents reported in the survey was compared to the respondent profiles provided by the marketing research companies. A response was considered invalid if inconsistent age information were found.
- **Spending enough time on the survey.** The time cutoffs were set to 10 min and 15 min respectively for the non-adopter and adopter versions of the survey. These time cutoffs were selected by the researchers as the fastest time they themselves could complete the survey while still reading all questions and providing meaningful answers.

3.3.3 Data Analysis

Two models were used to analyze the results of the discrete choice experiments: the Hierarchical Bayes (HB) model and the logit model [136].

An HB model uses Bayesian procedures to estimate parameters of a mixed logit model, which describes the choice probability as:

$$P_{ni} = \int \frac{exp(\beta x_{ni})}{\sum_j exp(\beta x_{nj})} f(\beta) d\beta \tag{3.1}$$

where P_{ni} is the probability of person n choosing option i from a pool of options js; x_{ni} is the vector of the attribute levels of option i that person n has; and β is the vector of the corresponding coefficients. The elements of vector β are random variables following distribution $f(\beta)$, representing the preference heterogeneity among the population. In this study, HB models were used to capture the overall preferences of the survey respondents. We assume β follows normal distributions.

A standard logit model is a special case of a mixed logit model, where the coefficient β is degenerate at fixed parameter b. In consequence, its choice probability becomes:

$$P_{ni} = \frac{exp(\beta x_{ni})}{\sum_j exp(\beta x_{nj})} \tag{3.2}$$

In this study, logit models were used when investigating the interaction effect between respondents' demographics and their choice patterns. Including interaction effects increased the number of explanatory variables of the models. To prevent overfitting, logit models were used instead of HB models for simplicity.

The importance of an attribute was calculated as the relative range in that attribute's utility values [137]. The importance values of all attributes of a model should add up to one. For the HB models, the attribute importance was first calculated on individual levels and then summarized as the mean and standard deviation over all respondents.

3.4 Results

3.4.1 Study Participants

In total, 2633 complete responses were received and 1773 responses passed all quality control rules, 1053 from California and 720 from Massachusetts. The number of responses from solar PV adopters and non-adopters from each state and distributions of their gender, age, and yearly household income are summarized in Table 3.2. Since we intentionally invited solar owners to take the survey, the proportions of the adopters to non-adopters do not reflect those among the general US population.

Table 3.2: Demographic distributions of survey respondents

	California		**Massachusetts**	
	Adopters	**Non-Adopters**	**Adopters**	**Non-Adopters**
Total	303	750	260	460
Gender				
Female	132 (43.6%)	461 (61.5%)	92 (35.4%)	302 (65.7%)
Male	171 (56.4%)	288 (38.4%)	163 (62.7%)	155 (33.7%)
Self-defined	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (0.7%)
Prefer not to answer	0 (0.0%)	1 (0.1%)	5 (1.9%)	0 (0.0%)
Age				
18-24	11 (3.6%)	53 (7.1%)	9 (3.5%)	28 (6.1%)
25-34	33 (10.9%)	114 (15.2%)	21 (8.1%)	80 (17.4%)
35-44	43 (14.2%)	157 (20.9%)	60 (23.1%)	102 (22.2%)
45-54	52 (17.2%)	175 (23.3%)	65 (25.0%)	99 (21.5%)
55-64	72 (23.8%)	143 (19.1%)	48 (18.5%)	91 (19.8%)
≥65	90 (29.7%)	101 (13.5%)	51 (19.6%)	59 (12.8%)
Prefer not to answer	2 (0.7%)	7 (0.9%)	6 (2.3%)	1 (0.2%)
Household Income (at the time when adopting solar, if solar owner)				
$\leq \$24,999$	3 (1.0%)	39 (5.2%)	3 (1.2%)	17 (3.7%)
$\$25,000 - 49,999$	25 (8.3%)	132 (17.6%)	9 (3.5%)	77 (16.7%)
$\$50,000 - 99,999$	82 (27.1%)	298 (39.7%)	39 (15.0%)	176 (38.3%)
$\$100,000 - 199,999$	124 (40.9%)	200 (26.7%)	110 (42.3%)	143 (31.1%)
$\geq \$20,000$	44 (14.5%)	45 (6.0%)	68 (26.2%)	19 (4.1%)
Prefer not to answer	25 (8.3%)	36 (4.8%)	31 (11.9%)	28 (6.1%)

3.4.2 Discrete Choice Analysis with HB Models

The part-worth utilities of each attribute level was estimated with a HB model. Effect coding was used so that the summation of the level part-worths of an attribute would equal to zero. When estimating each model, 100,000 iterations were performed and the first 50,000 iterations were considered burn-in (allowing the simulation to reach its equilibrium) [136]. After convergence, every tenth draw was retained, resulting in 5,000 iterations for calculating the part-worths. The results are summarized in Table 3.3 and visualized in Figure 3-2. The overall trends of the part-worths were consistent with our expectations.

The mean part-worths of the "None" options were negative in both the installer and system choice models, indicating overall the respondents were more likely to choose an installer or system option instead of a "None" option. However, the part-worth standard deviations were large, indicating large variation among the respondents.

In the installer discrete choice experiment, higher independent reviewer rating, longer warranty, and higher savings had higher mean part-worths. In addition, the error bars of the highest and the lowest levels of these attributes did not overlap with the x-axis of 0, indicating the majority of the respondents had consistent preference trends. Among the three collaboration styles, Independent was on average the least preferred and Collaborative was on average the most preferred. However, the standard deviations of their part-worths were larger than the means, indicating a large preference variation as a significant number of respondents still preferred an independent style over a collaborative one. This result was also reflected in the interviews with the solar owners, that some solar owners had strong opinions on system design and would prefer their systems to be custom made, while others preferred installers to make all installation decisions for them. For panel technologies, the cutting-edge had the highest and the traditional had the lowest mean part-worths, indicating the more advanced technology was, in general, more preferred. Again, there was large variation among the respondents. Since the cutting-edge technology was on the market for less time compared to standard and traditional technology, it was likely that some respondents would prefer the traditional technology to avoid potential risk. Overall, the longer the project time was, the lower its mean part-worth would be. However, the difference between the part-worths of 1/2 month and 1 month was small, suggesting that a 1-month project time was short enough for homeowners in general, and further shortening the project time might not provide extra benefits.

For solar systems, the higher the efficiency, the less frequent the failures, the larger the environmental benefit, and again the higher the savings, the higher the mean part-worths. In addition, the respondents generally preferred micro-inverters over power optimizers and preferred both of them over central inverters. On average, the respondents preferred low

Table 3.3: Estimated part-worths of HB models

	Installer			System	
	Mean	**St Dev**		**Mean**	**St Dev**
	(se)	**(se)**		**(se)**	**(se)**
None	-1.008 (0.116)	4.035 (0.111)	None	-0.748 (0.117)	4.236 (0.120)
Independent reviewer rating: 3 stars	-1.429 (0.038)	1.016 (0.039)	Efficiency: 15.5%	-0.902 (0.037)	0.912 (0.048)
Independent reviewer rating: 4 stars	0.294 (0.022)	0.457 (0.026)	Efficiency: 18.0%	-0.470 (0.032)	0.608 (0.041)
Collaboration: independent	-0.232 (0.021)	0.464 (0.027)	Efficiency: 20.5%	0.216 (0.034)	0.374 (0.033)
Collaboration: moderately collaborative	0.076 (0.018)	0.287 (0.021)	Efficiency: 23.0%	0.531 (0.029)	0.542 (0.036)
Technology: cutting-edge	0.206 (0.026)	0.751 (0.029)	Visibility: high	-0.306 (0.024)	0.771 (0.025)
Technology: standard	-0.014 (0.023)	0.459 (0.028)	Inverter: central	-0.737 (0.036)	1.098 (0.040)
Project time: 1/2 month	0.258 (0.025)	0.461 (0.034)	Inverter: micro	0.548 (0.033)	1.076 (0.034)
Project time: 1 month	0.275 (0.024)	0.349 (0.026)	Failures: 0	1.530 (0.048)	1.542 (0.048)
Project time: 2 months	-0.006 (0.019)	0.313 (0.026)	Failures: 1	0.714 (0.026)	0.500 (0.032)
Warranty: 5 years	-1.834 (0.047)	1.327 (0.045)	Failures: 2	-0.604 (0.026)	0.612 (0.032)
Warranty: 15 years	0.432 (0.024)	0.464 (0.029)	Environmental benefit: 3 acres of forest	-0.459 (0.026)	0.662 (0.032)
Savings: 10%	-3.440 (0.079)	2.109 (0.072)	Environmental benefit: 6 acres of forest	0.136 (0.02)	0.259 (0.023)
Savings: 25%	-0.954 (0.037)	0.846 (0.041)	Savings: 10%	-3.830 (0.093)	2.611 (0.085)
Savings: 40%	0.480 (0.03)	0.425 (0.038)	Savings: 25%	-0.920 (0.039)	0.976 (0.043)
Savings: 55%	1.152 (0.043)	0.877 (0.038)	Savings: 40%	0.586 (0.029)	0.442 (0.038)
			Savings: 55%	1.358 (0.045)	1.105 (0.048)
Log-likelihood	-11598.22		Log-likelihood	-10394.01	

Note: the log-likelihoods were calculated at the mean individual-level coefficients across iterations.

panel visibility better than high panel visibility, which was consistent with previous findings that solar panels which visually blend into the roof were considered more aesthetically pleasing [112]. However, again, the part-worths' standard deviations were large, indicating there existed a significant proportion of respondents who preferred high panel visibility over low panel visibility.

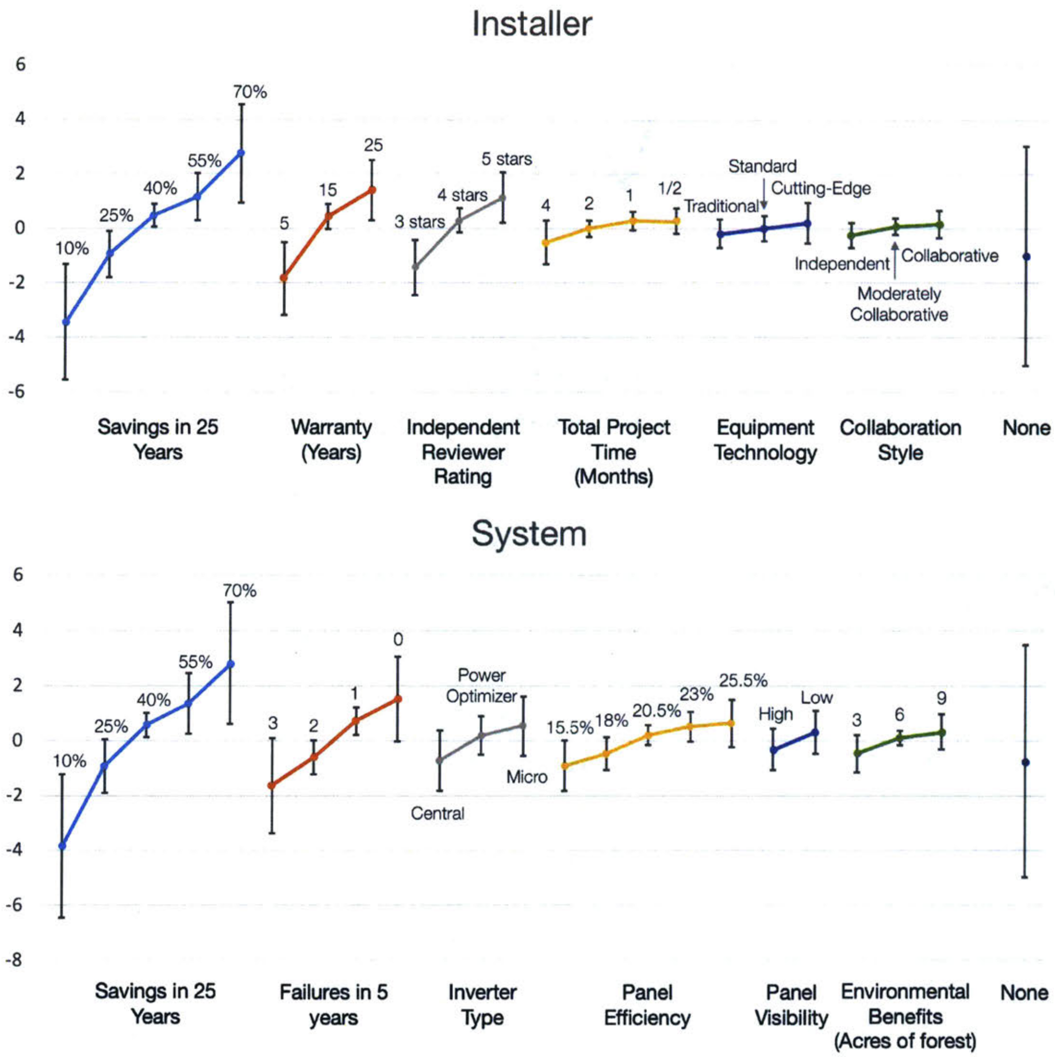


Figure 3-2: Estimated part-worths of the solar installer discrete choice experiment (above) and solar system discrete choice experiment (below) using HB models.

Note: Error bars represent the part-worth standard deviations. The attributes are presented in order from the most important (left) to the least important (right).

The attribute importance is summarized in Table 3.4. Savings were by far the most important attributes of both installers and solar PV systems. The average importance values of Savings were more than 40%, much higher than any other attributes. This result was not surprising considering that a major motivation for homeowners to adopt solar was to save electricity bills [93].

Warranty and the number of failures in five years were respectively the second most important attributes of the installer and system discrete choice, each with around 22% mean importance values. In contrast, the overall equipment technology, the panel efficiency, and the inverter type had lower importance values. These unexpected results suggest that homeowners care more about the system reliability and ease of maintenance than technology advancement per se. The low importance of panel efficiency was surprising and contradictory to a previous study which found that efficiency was the second most important factor in panel selection decisions [85]. One potential explanation was that the exact value of panel efficiency was a technical term that was hard to perceive by the average homeowner. The benefit of high panel efficiency could be perceived as higher energy production and consequently more energy bill savings, as does the benefit of micro-inverters and power optimizers. Therefore, unless a customer was technology savvy, they might not care much about the exact technical details of a solar system, but instead focus on the overall savings provided by the system.

Independent reviewer rating was found to be very important in the installer discrete choice experiment. This was consistent with findings of previous studies that the recommendation from professionals was important to the consumers' adoption decision regarding micro-generations [121] and energy products [138]. Interestingly, the environmental benefit had a low importance value, even though being environmentally sustainable was another important motivation for homeowners to adopt solar [98, 122].

Table 3.4: Attribute importance

	Installer		**System**	
Rank	**Attribute**	**Importance (mean ± sd)**	**Attributes**	**Importance (mean ± sd)**
1	Savings	41.0 ± 14.2%	Savings	40.8 ± 17.9%
2	Warranty	22.0 ± 10.4%	Failures in 5 years	22.1 ± 14.8%
3	Independent reviewer rating	19.4 ± 12.0%	Inverter	12.0 ± 9.1%
4	Project time	6.9 ± 4.8%	Efficiency	11.5 ± 8.1%
5	Technology	6.3 ± 6.1%	Visibility	7.0 ± 7.7%
6	Installer-customer collaboration	4.5 ± 4.1%	Environmental benefit	6.5 ± 5.1%

3.4.3 Interactions Between Respondent Demographics and Attribute Preferences

To detect the potential influence of respondents' demographics on their preferences for solar installers and systems, interaction terms between the demographics and the solar attributes were estimated using logit models. Demographic variables including the state, solar ownership, yearly household income, and age were considered. Linear utilities instead of part-worth utilities were estimated for continuous attributes for two reasons: firstly, the previous HB modeling results demonstrated that the part-worth utilities of these attributes had linear trends; secondly, the inclusion of interaction terms largely increased the models' number of explanatory variables, and estimating linear utilities for continuous variables helped simplify the models and prevent overfitting. Main effects of the logit models are summarized in Table 3.5 and interaction effects are summarized in Table 3.6. The most significant interaction effects (p-value < 0.001) are discussed below.

Table 3.5: Logit model main effects

	Installer			**System**	
	β	**p-value**		β	**p-value**
None	-0.165	<0.001	None	-0.016	0.373
Reviewer rating	0.652	<0.001	Efficiency	0.076	<0.001
Collaboration: independent	-0.139	<0.001	Visibility: high	-0.135	<0.001
Collaboration: moderately	0.049	<0.001	Inverter: central	-0.333	<0.001
Technology: cutting-edge	0.148	<0.001	Inverter: micro	0.258	<0.001
Technology: standard	0.000	0.989	Failures	0.496	<0.001
Project time	-0.123	<0.001	Environmental benefit	0.077	<0.001
Warranty	0.077	<0.001	Savings	0.045	<0.001
Savings	0.050	<0.001			
Interaction Effect	w/o	w/		w/o	w/
Log-likelihood	-30704	-30036		-32958	-32453
AIC	61426	60162		65932	64986
BIC	61500	60533		65998	65316

In the installer choice experiment, homeowners' ages had significant and positive interaction with installer warranty, indicating older homeowners more strongly preferred longer warranties over shorter warranties than younger homeowners did. Reviewer rating had significant and positive interaction with homeowners' household income, suggesting higher income homeowners tended to prefer more of the higher rated installers than lower-income homeowners did. These two interactions are visualized in Figure 3-3. Each dot is a part-worth of an attribute level, estimated within each age group or income group. Stratification was applied and estimations were conducted within adopter or non-adopter groups in each state to control for potential confounding effects between the domographic variables.

Table 3.6: Logit model interaction effects between respondent demographics and solar attributes

	Installer			System	
	β	p-value		β	p-value
Age			**Age**		
×None	0.520	<0.001	×None	0.434	<0.001
×Reviewer rating	-0.017	0.105	×Efficiency	-0.005	0.041
×Collaboration: independent	-0.021	0.087	×High visibility	-0.056	<0.001
×Collaboration: moderately	-0.012	0.310	×Inverter: central	-0.074	<0.001
×Technology: cutting-edge	-0.013	0.285	×Inverter: micro	0.074	<0.001
×Technology: standard	0.005	0.677	×Failures	0.011	0.182
×Project time	-0.021	0.001	×Environmental benefit	-0.004	0.198
×Warranty	0.014	<0.001	×Savings	0.001	0.204
×Savings	0.000	0.718			
Income			**Income**		
×None	0.109	<0.001	×None	0.019	0.019
×Reviewer rating	0.040	<0.001	×Efficiency	0.001	0.769
×Collaboration: independent	-0.009	0.500	×High visibility	-0.051	<0.001
×Collaboration: moderately	0.001	0.966	×Inverter: central	-0.007	0.590
×Technology: cutting-edge	0.043	<0.001	×Inverter: micro	0.013	0.274
×Technology: standard	-0.011	0.363	×Failures	-0.004	0.593
×Project time	0.010	0.131	×Environmental benefit	-0.004	0.226
×Warranty	0.001	0.585	×Savings	0.002	0.004
×Savings	0.001	0.237			
State			**State**		
×None	-0.017	0.322	×None	-0.013	0.405
×Reviewer rating	-0.006	0.606	×Efficiency	0.002	0.385
×Collaboration: independent	0.053	<0.001	×High visibility	0.019	0.024
×Collaboration: moderately	-0.030	0.013	×Inverter: central	0.045	<0.001
×Technology: cutting-edge	0.024	0.044	×Inverter: micro	-0.030	0.007
×Technology: standard	-0.035	0.005	×Failures	0.006	0.422
×Project time	-0.009	0.160	×Environmental benefit	-0.018	<0.001
×Warranty	0.000	0.897	×Savings	-0.001	0.017
×Savings	-0.004	<0.001			
Solar			**Solar**		
×None	0.105	<0.001	×None	0.035	0.048
×Reviewer rating	-0.034	0.005	×Efficiency	0.003	0.328
×Collaboration: independent	-0.019	0.173	×High visibility	0.059	<0.001
×Collaboration: moderately	0.018	0.195	×Inverter: central	0.039	0.004
×Technology: cutting-edge	0.008	0.559	×Inverter: micro	-0.027	0.032
×Technology: standard	0.021	0.131	×Failures	-0.010	0.271
×Project time	0.015	0.053	×Environmental benefit	0.017	<0.001
×Warranty	0.003	0.027	×Savings	0.001	0.058
×Savings	0.001	0.085			

Notes: Effect coding was used for categorical demographic variables. California was coded as 1 and Massachusetts was coded as -1; a solar adopter was coded as 1 and a non-adopter was coded as -1. Income and age were treated as continuous variables and were normalized to center at 0. These made sure that the estimates of the model main effect would still represent the average preferences of the population. Responses to income and age questions that were "not prefer to answer" were replaced with the median values of the population.

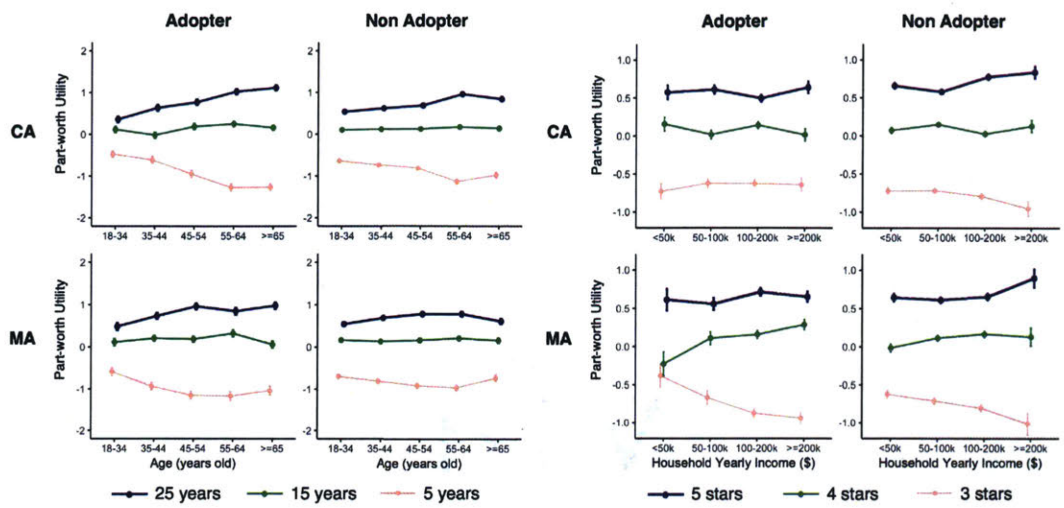


Figure 3-3: Interactions between age and warranty (left) and income and independent reviewer rating (right)

It was also found that the interaction effect between cutting-edge technology and homeowners' household income was significant and positive, the interaction between independent collaboration style and state was significant and positive, and the interaction between savings and state was significant and negative. These suggested that higher income homeowners tended to prefer more of the cutting-edge technology compared to lower income homeowners. Massachusetts homeowners preferred installers to work more collaboratively than independently compared to California homeowners. And California homeowners cared a little less about the savings compared to Massachusetts Homeowners.

In addition, the "None" option significantly and positively interacted with respondents' age, income and solar ownership. This suggested that older homeowners, higher income homeowners, and current solar owners tended to choose "None" options more often than younger homeowners, lower income homeowners, and non-adopters, reflecting more rigorous standards of the prior groups for selecting solar installers.

In the system choice experiment, the high panel visibility negatively interacted with age and income (Figure 3-4). Regardless of the state that homeowners resided in and their solar ownership, consistent trends could be observed that older and higher income homeowners had much stronger preferences for low panel visibility over high panel visibility. However, among younger and lower income homeowners, the differences between preferences for the low and high panel visibility were smaller. In the $< \$50k$ income groups among adopters in both states, the average utilities of the high panel visibility were even higher than those of the low panel visibility. One potential explanation is that, older and higher income homeowners tended to be concerned more about the aesthetics of their homes and thus preferred less visible panels, while younger and lower income homeowners preferred the panels to be more observable to make statements about their environmental beliefs [74]. Another interpretation of this result might stem from the fact that solar panels are a technology that have grown significantly in adoption in the past 10 years [139] and in that time younger homeowners have grown accustomed to the appearance of panels on a roof in a way that older homeowners who grew up an earlier era aren't. After controlling the effect of age and income, solar adopters on average preferred low visibility panels over high visibility panels not as strongly as non-adopters did.

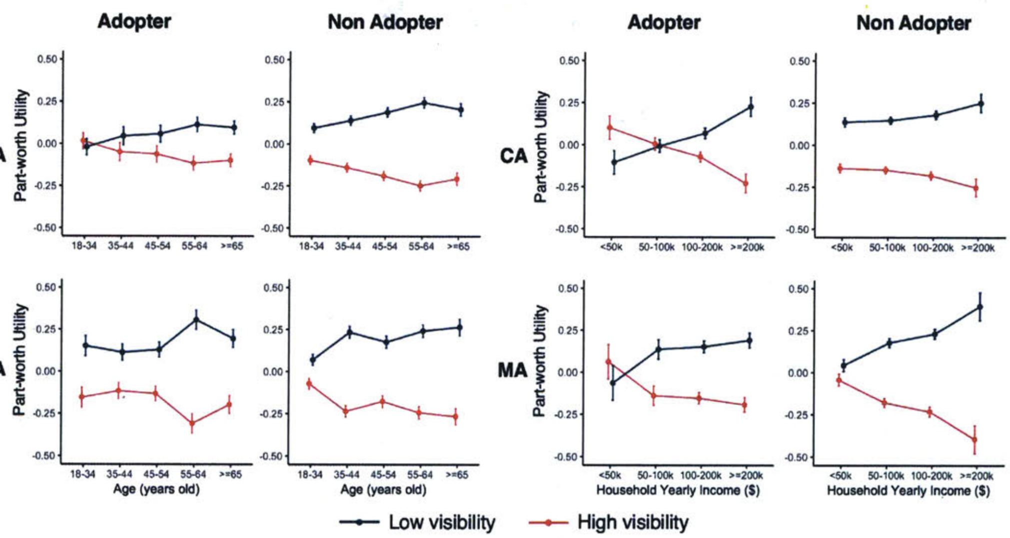


Figure 3-4: Interactions between age and panel visibility (left) and income and panel visibility (right)

In addition, type of inverters was found to have significant interaction effects with age and state: older homeowners had stronger preferences for micro-inverters and lower preference for central inverters compared to younger homeowners. Massachusetts homeowners had lower preference for central inverters compared to California homeowners. Significant interactions between solar systems' environmental benefit and state and solar ownership indicated that Massachusetts homeowners and solar owners on average cared more about the environmental benefit of a solar system compared to California homeowners and non-adopters, respectively. Again, the "None" option had significant interaction effects with age, showing older homeowners were more likely to choose the "None" options compared to younger homeowners.

3.5 Discussion

Q1: How do homeowners make tradeoffs between different attributes of solar PV systems and solar installers?

In this chapter, a subset of key features of solar PV systems and installation identified via stakeholder interviews were evaluated with two discrete choice experiments. Savings was by far the most important concerns in both the installer and system discrete choice experiments. This was not surprising at all, considering that a major motivation for current homeowners to adopt solar is to save on electricity bills. Installer's warranty and system failure rate were the second most important attributes in the installer and the system discrete choice experiments, respectively. This indicated a tendency of risk aversion of homeowners. Technology advancement, such as solar panel efficiency and inverter types, was not as important.

Consistent with our expectation, homeowners preferred installers who had better reviews, provided longer warranties and higher savings, and could install solar faster. Overall, a collaborative installer working style was preferred over independent working style and cutting-edge technology was preferred over traditional technology; however, large variations existed among the population. For a solar system, higher panel efficiency, lower failure rate, higher environmental benefit and higher savings were more preferred. Micro-inverters were preferred over power optimizers, which were preferred over central inverters. Low panel visibility was, in general, preferred over high panel visibility.

Q2: How do preferences for solar PV systems and solar installers compare across homeowner demographics?

All the four demographic attributes investigated (state, solar ownership, income, and age) appeared to cast influences on homeowners' preferences for solar installers and systems. California homeowners on average cared less about if an installer work collaboratively or independently, and they cared less about the type of inverters, compared to Massachusetts homeowners. Higher income homeowners had stronger preference for the "delight features" of solar, such as cutting-edge equipment technology or low panel visibility. These results show the necessity of diversifying solar product and service features in order to appeal to different market segments. In addition, the preference of the current solar owners, who are presumably the early adopters of the technology, tended to be different from the current non-adopters, some of whom might adopt solar in the near future. On one hand, it is important for solar installers and manufacturers to keep improving their products and services in order to respond to the changing market. On the other hand, education might be necessary for non-adopters to overcome any perceptual barriers to the adoption of solar PV.

3.6 Conclusion

In this chapter, a survey was designed based on the interview results described in the previous chapter and was deployed to more than 1,700 homeowners in two states of the US. Two discrete choice experiments were conducted with both solar adopters and non-adopters, the results of which provide understanding of how homeowners made tradeoffs between different attributes of solar systems and installers.

This study differentiates from the existing literature because it takes a user-centered product design perspective and focuses on non-financial design level attributes of both the solar systems and the solar installation. Data were collected from thousands of homeowners including both solar adopters and non-adopters, and the survey was distributed in two US states, enabling comparison between different demographic groups and provided more comprehensive understanding of US homeowners' needs and preferences for solar PV.

The findings of the studies are useful to manufacturers to guide the design of their products and are valuable to installers to inform the design of their services. In addition, these results can help calibrate simulation models for predicting future solar adoption and analyzing impact of policies on the solar market, which will provide insights to policy makers regarding how to effectively further the diffusion of solar PV technology among homeowners.

Chapter 4

Balancing the Quantitative and the Emotional in Eco-Feedback Designs

4.1 Motivation

This chapter and the next focus on investigating the design of eco-feedback products. The studies take the perspective that a successful eco-designed product need to not only provide environmental benefits but also appeal to users and customers [15].

Traditionally, resource usage information in eco-feedback products is presented quantitatively [83] with the expectation that rational users, who make decisions to maximize their net benefit, will behave environmentally consciously once they are made aware of the environmental consequences of their behavior. For example, some cars are equipped with fuel economy meters that present the numerical miles-per-gallon of a vehicle under the assumption that drivers will change their driving patterns accordingly to save fuel and reduce greenhouse gas emission. However, this assumption may fail in practice and one study suggests that quantitative information tends to be effective only on those who already have strong pro-environmental intentions [33]. In contrast, in a prevailing notion from the area of Emotional Design as discussed in Chapter 1, a successful product should not only have high functional performance but also deliver strong emotional value [59, 61]. Based on these, we hypothesize that an eco-feedback design that is more emotionally engaging [72] will make the product more appealing to users.

This chapter compares two key aspects of the way resource usage information can be presented in eco-feedback products: being quantitative and being emotionally evocative, and examines how they influence user perceptions and preferences. The research questions are:

Q1: How are quantitative and emotionally evocative usage information presented in an *eco-feedback product linked to users' perceptions of the appeal of the overall design and its effectiveness in encouraging sustainable behavior?*

We believe both quantitative and emotionally evocative aspects of resource usage can influence user perception, and expect that designs that present more quantitative resource usage information or evoke stronger emotions will be more appealing to users and be perceived as more effective in encouraging pro-environmental behaviors.

Q2: Do users with different levels of environmental awareness or quantitative resource consumption knowledge, or with different demographic background respond differently to the quantitative and emotional aspects of resource usage information presented in an eco-feedback product?

Previous studies have offered evidence that users who have different levels of environmental awareness and knowledge [55], motivations for sustainable behaviors [140], and social orientations (pro-social or pro-self) [141] tend to react differently to eco-feedback designs. Thus we consider preference heterogeneity among users, that not all people like the same designs [142, 143], and aim to identify design approaches specifically for different user groups.

4.2 Related Work

This chapter focuses on the eco-feedback strategy which presents users with information about resource consumption or environmental impact caused by product use [35, 82, 144, 145]. An example of eco-feedback is an energy monitoring system that provides feedback on household electricity usage [146]. Another example is a beverage package labelled with an anti-littering message [147]. Both of these have been proven effective in promoting pro-environmental behaviors such as conservation of energy and reducing litter.

Seemingly small, but critical, details of a product's design can strongly impact whether a product is used effectively or whether a product is perceived as environmentally sustainable [148]. For eco-feedback products, the way resource usage information presented in a product is a key design concern [72, 83] and subtleties in information presentation can make significant impact on user perceptions. For example, presenting a ranking of an individual's consumption within a population versus presenting consumption relative to the population average would make a difference [149].

A substantial number of studies investigate the effectiveness of the eco-feedback strategy alongside user perceptions of the resulting designs. Montazeri, et al. [57] created napkin dispensers that displayed the quantity of napkins used, and validated each design's effectiveness at reducing consumption in a field study. In another study, they used both an online survey and in-lab experiment to show that the colors of the recycling bins play important role in the effectiveness of encouraging recycling behaviors [54]. Cor and Zwolinski [55] tested four coffee makers intended to encourage electricity conservation. They found that the eco-feedback design (which reported energy consumed while making coffee) and the goal setting design (which provided a target value for energy consumption) were perceived as more useful and less intrusive than a written-information design (which offered instructions for turning off the coffee maker) or a smart design (which switched off the coffee maker automatically). Sohn, et al. [53] evaluated ten water faucet and sink designs intended to encourage water conservation. Immediate user reactions suggested that displaying water usage information raised more awareness and was perceived as more effective for encouraging water conservation than applying physical constraints that reduced water use. Wever et al. studied the household usage of an energy meter and applied a user-centered design strategy to improve its usability [150].

The studies described above each tested the designs of a single product only. In this study, we explore effectiveness of eco-feedback across several different scenarios. Specifically, we systematically compares four design techniques over eight products.

4.3 Methods

Overview: In total, thirty-two designs of eight eco-feedback products were generated. Surveys were distributed among students in five universities in two countries. Potential links between survey respondents' preferences for specific designs to their personal characteristics, including gender, environmental awareness, and knowledge of resource consumption were examined.

4.3.1 Eco-Feedback Designs

Though many environment-related fields are worthy of study, a subset was selected that was directly linked to both the consumption of nature resources and the everyday lives of the general public: Electricity, Materials, Transportation, and Water. In addition, these categories were general enough to allow for a diverse range of products. Two products in each category were chosen: one providing feedback on resource usage and the other presenting information that encourages a user to carry out sustainable behaviors.

Electricity:

- An **Electricity Meter** that monitors home electricity usage
- A **Light Switch** that reminds people to turn off the lights when leaving a room

Materials:

- A **Paper Towel Dispenser** that tracks how many paper towels have been consumed

- **Waste Cans** that separate landfill, recyclables and compostable waste

Transportation:

- A **Fuel Economy Meter** that tracks the miles-per-gallon (MPG) of a vehicle
- A **Public-Transport Poster** that encourages the use of public transportation

Water:

- A **Water Faucet** that monitors the day's cumulative water usage
- A **Washing Machine** with a selectable water-saving mode

These products take their inspiration from the literature and a range of industrial design examples [35, 36, 53, 55, 57, 151, 152], and were believed to be products that student respondents would likely be familiar with. Visual representations of four versions of each of the products were generated, taking the following forms, respectively:

- **Text or Chart** displays resource usage information with clear, quantitative data
- **Visual Emphasis** attracts user's attention through strong visual elements
- **Metaphor Using Objects** includes inanimate objects related to the environment or to resource consumption
- **Metaphor Using Living Creatures** incorporates animals or plants as reminders of the environment and resource usage

These design forms were drawn from existing literature and aimed to cover a range from quantitative to emotionally evocative. *Text or chart* is a design approach widely used in products such as water or energy dashboards [83, 153]. *Visual emphasis* draws on a basic technique in graphic and user interface design [154] that attracts a user's attention to information through graphical elements. Examples include the battery icon on a mobile device, which turns red when the battery runs low. *Metaphor* is another common approach in user interface design [155], which makes analogies between the design and other concepts. It had been used in many product-led interventions for sustainable behavior [57, 72, 152]. Two types of *metaphors* were explored in this study: *metaphor using inanimate objects*, e.g. using a light bulb as indicator of energy consumption, and *metaphor using living creatures*, e.g. using an image of polar bear on a melting iceberg as reminder of global warming. It was anticipated that images of living creature would evoke stronger emotions such as empathy for animals suffering from climate change, or hope for our ability to avoid future environmental damage [156].

All designs are summarized in Figure 4-1 to Figure 4-4. Research suggests that when presenting representations to users, differences in fidelity and style can overshadow the

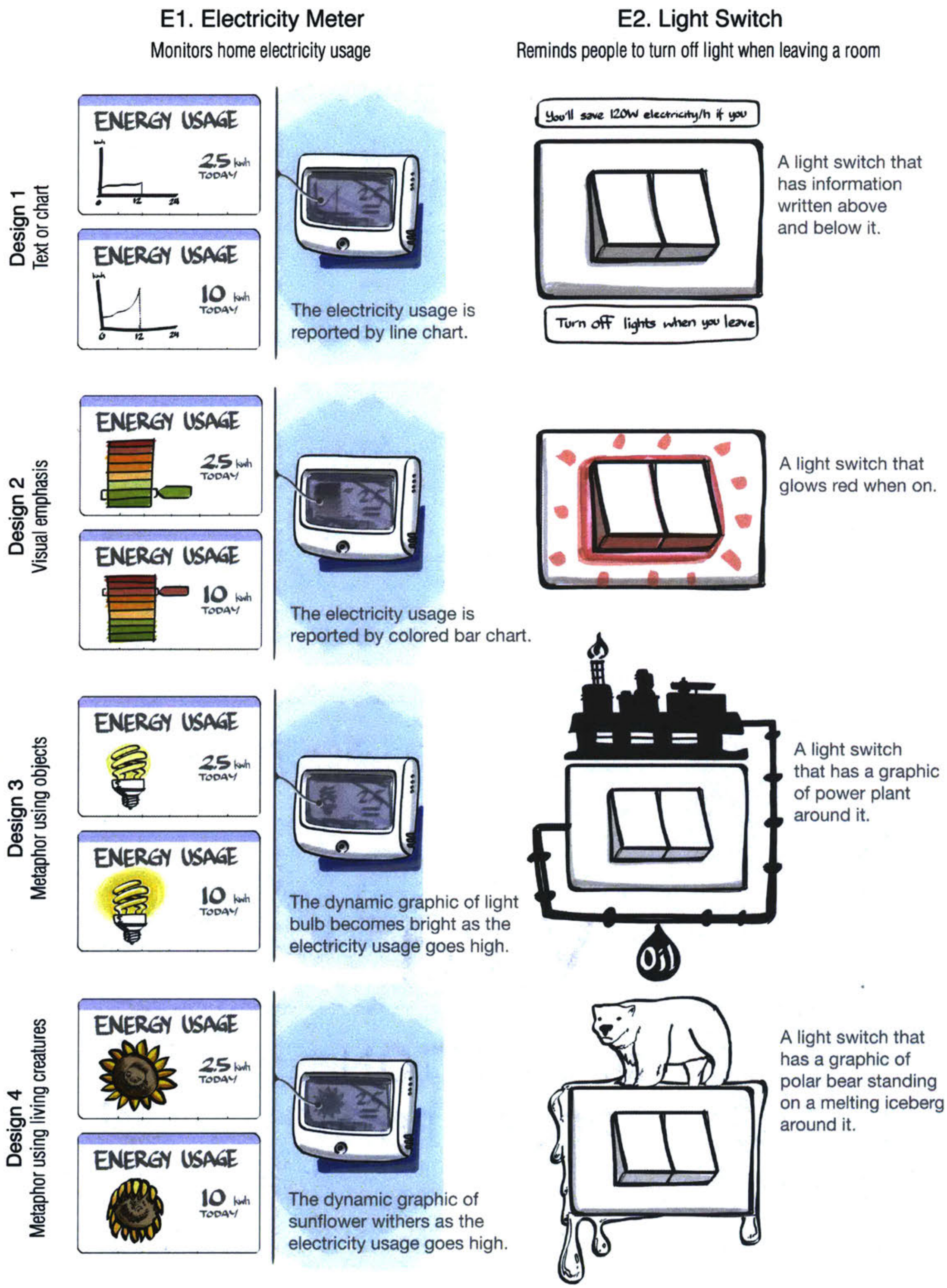


Figure 4-1: Electricity conservation designs

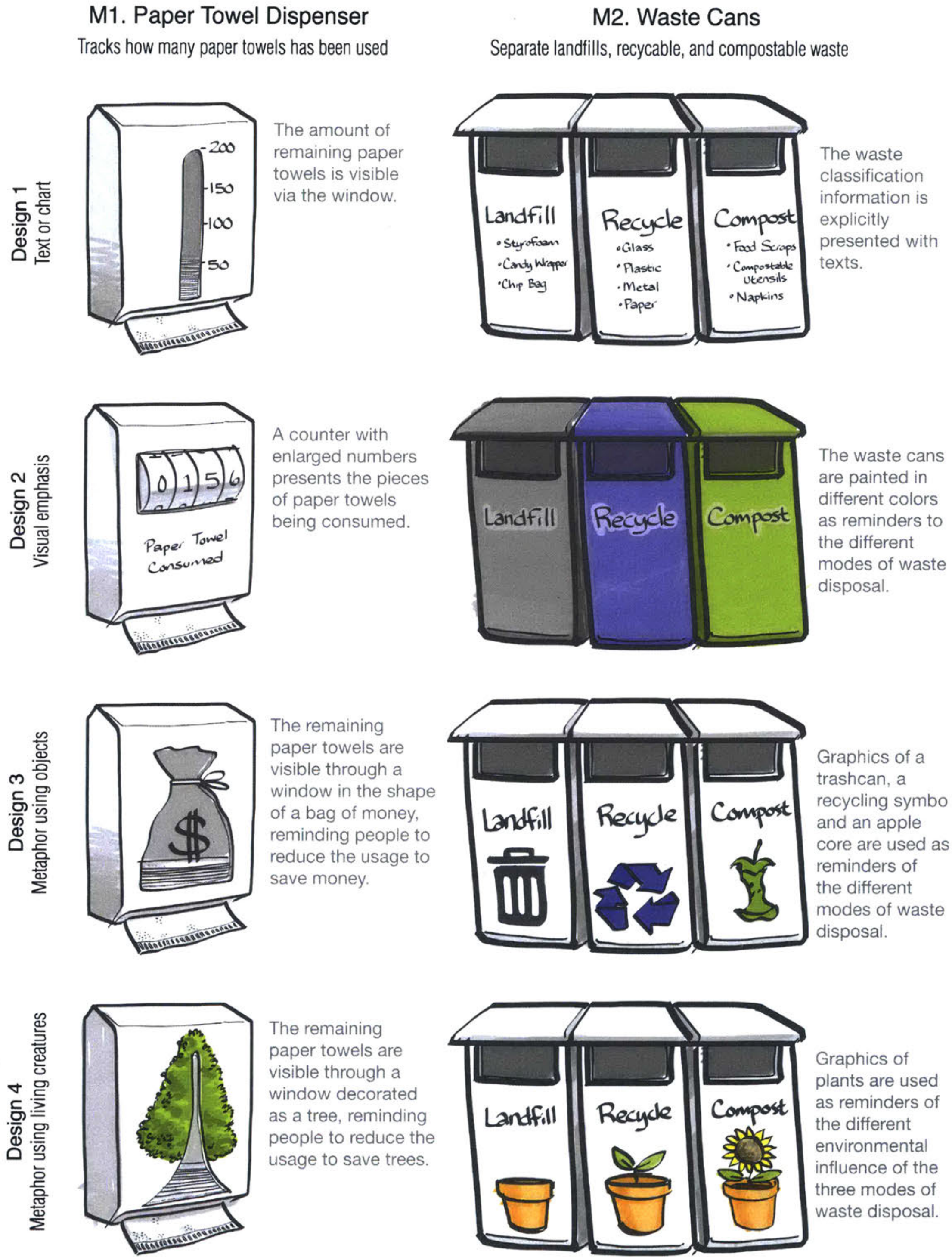


Figure 4-2: Material conservation designs

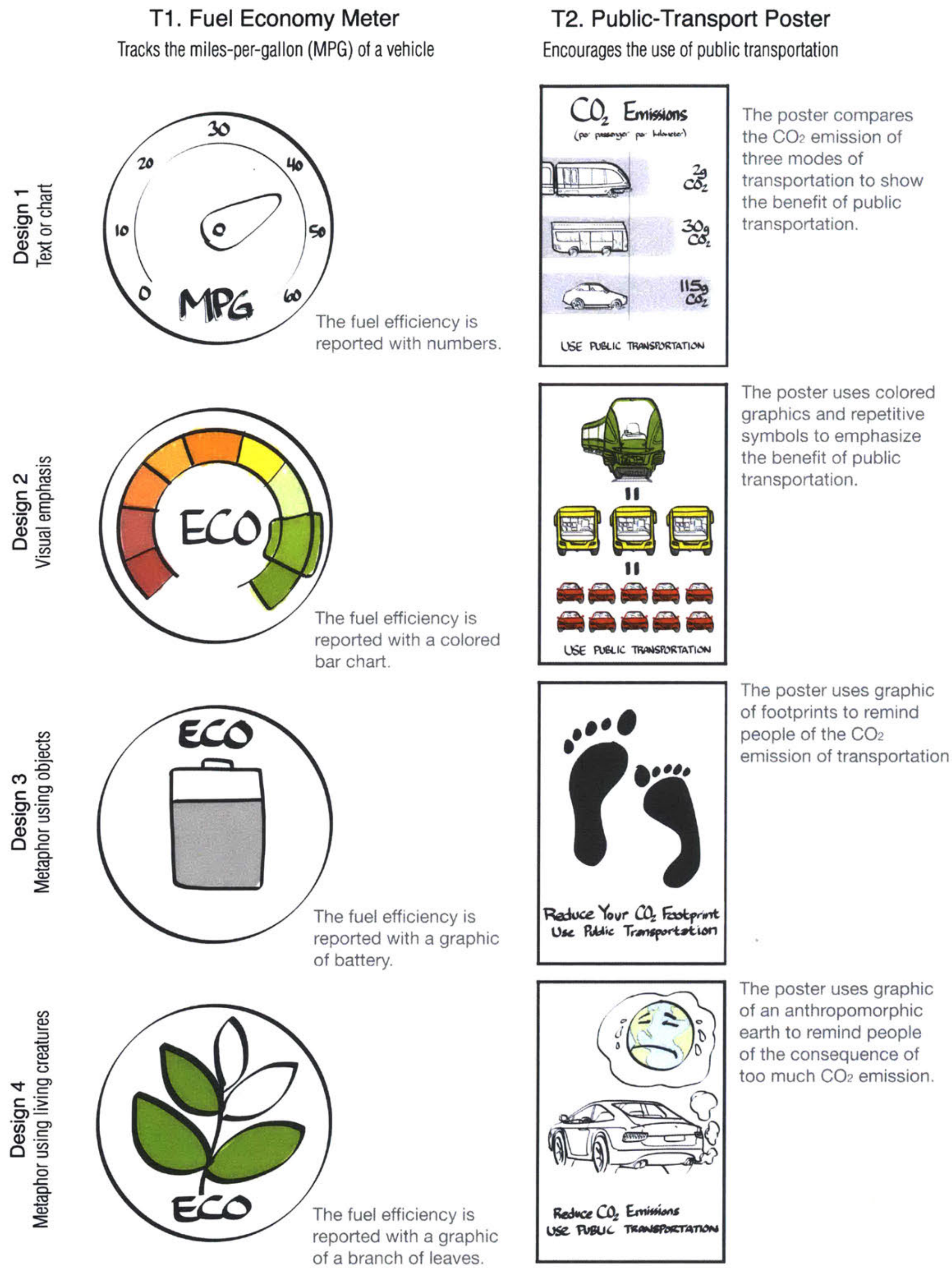


Figure 4-3: Transportation fuel conservation designs

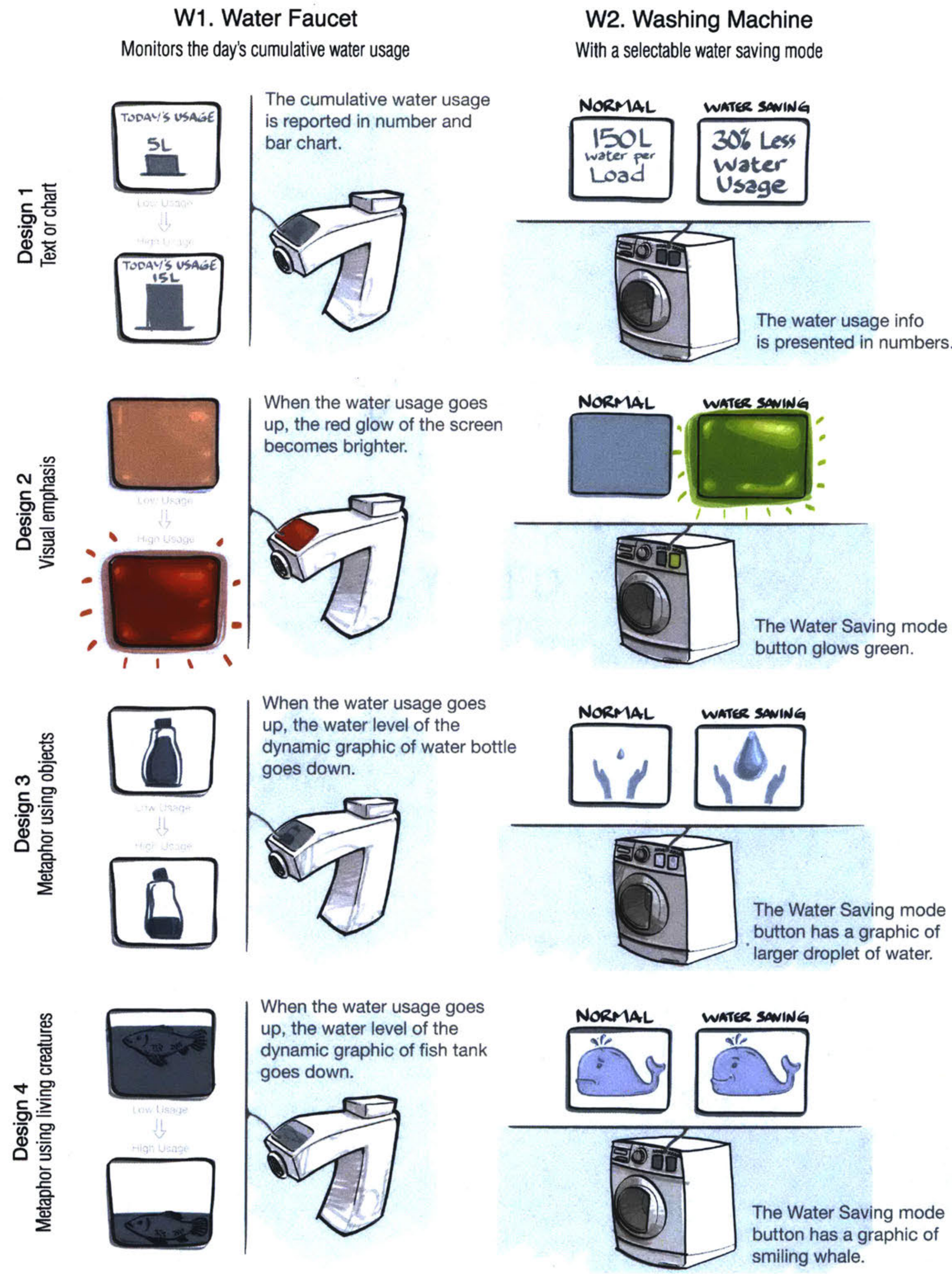


Figure 4-4: Water conservation designs

content of a design [157]. Thus these designs were hand-sketched by a single professional industrial designer to maintain a consistent visual style to mitigate potential evaluation bias [51].

4.3.2 Survey Development and Implementation

A survey was constructed to ask respondents to evaluate and provide feedback on the eco-feedback designs. In addition, the survey evaluated the respondent's ability to estimate resources used in common daily activities and their awareness of environmental sustainability. Demographics including age, gender, year of school, major, university and nationality were collected.

In order to avoid survey fatigue by presenting respondents with all thirty-two designs in a single survey, four distinct versions of the survey were created, each focusing on one resource category. Each respondent was randomly assigned to one version of the survey, and was presented with resource estimation questions and in total eight designs of two products from one resource category. The awareness questions were the same across all surveys.

An online survey platform, Qualtrics, was used to create and deploy the survey. Pilot testing was conducted with four product design graduate students for timing, wording and reading level. Their feedback was used to refine the survey.

Part I: Resource Consumption Knowledge and Environmental Awareness

Respondents' knowledge regarding resource consumption in fields of Electricity, Materials, Transportation, or Water was evaluated. In the Electricity and Water versions, respondents were asked to estimate the electricity or water usage in common daily activities, such as using a laptop computer for an hour [158], or running a washing machine for one cycle. In the Materials version, respondents were asked to differentiate recyclable and compostable waste from landfill. For Transportation, respondents were asked to estimate the CO_2 emissions of different mode of transportation.

The usage and emission estimation questions were presented as logarithmic sliders to emphasize orders of magnitude rather than precise values. Respondents were not expected to know exact values for these activities, and thus were asked to give rough estimates. To aid estimation, reference points were provided, such as the electricity consumed by a single light bulb. Figure 4-5 shows examples of the usage estimation questions.

Respondents could choose to view the survey in either SI or Imperial units. Multiple online resources including the website of United States Environmental Protection Agency were referred to in developing answers for these questions (see Appendix C.1 for more information). For devices whose resource consumption may vary by model, brand or working

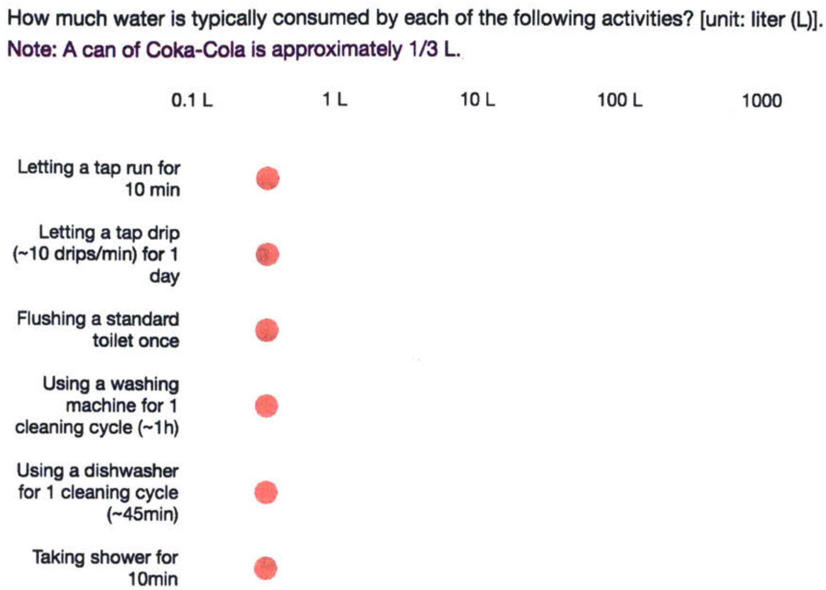


Figure 4-5: Examples of resource (water) usage estimation questions

condition, standard devices with typical consumption rates were selected as the reference.

Eight questions were used to evaluate the respondents' environmental awareness (see Appendix C.2): six asking the survey respondents to rate if they agreed or disagreed with statements regarding natural resources and the environment, and two asking the respondent to self-report their environmental awareness and the environmental friendliness of their lifestyle on 1-5 Likert scales. These questions were adapted from the New Ecological Paradigm scale [159], a widely used measure of environmental concern; and the section of Attari, et al.'s Survey on Energy [160] that measures environmental attitude.

Part II: Design Evaluation Questionnaire

The survey first presented the designs individually in random sequence and asked the respondents to rate the designs using 1-5 Likert scales on four criteria:

- **Clarity:** How clearly did the design show resource usage/How clearly did the design communicate the idea of encouraging sustainable behavior?
- **Emotion:** How strong an emotional response did the design evoke?
- **Effectiveness:** How effective would the design be in encouraging the respondent to behave in a more environmentally friendly way?
- **Appeal:** In general, how much did the respondent like the design?

Clarity and Emotion directly evaluate the two aspects of eco-feedback designs that are of interest in this study. Clarity is a measurement of how individuals perceive quantitative resource usage information, while Emotion measures the overall intensity of emotions evoked by the designs. Effectiveness looks at the designs' potential influence on user-product interaction behavior as assessed by respondents. Appeal is an overall evaluation of how attractive or desirable users find a design to be. The latter two criteria serve as evaluations for the perceived quality of the overall eco-feedback designs. Optional open-ended comment areas were provided for respondents to elaborate on their ratings. Examples of the design evaluation questions are presented in Figure 4-6.

We should note that all four criteria were subjective measurements from individual respondents, and thus variations of the ratings were expected. However, we believe there are intrinsic properties of the designs which guide the individual ratings: we expected that designs that presented quantitative resource usage would be more likely to be perceived as showing clear information; designs that were more emotionally evocative would be more likely to be perceived as evoking strong emotions; design that encourage more people to adopt sustainable behavior would overall receive higher ratings in effectiveness, and designs rated by more respondents as appealing would be more likely to gain market success. Therefore, the average ratings of these evaluation criteria were calculated for each design as inference to its intrinsic properties.

After individually rating each of four designs of one product, respondents were presented with all four designs at the same time in randomized sequence, and were asked to select one that they would choose for themselves, known as a "most preferred" choice [161, 162]. These choice questions simulated consumers selecting one product out of a group of similar products, with attempts to approximate their potential purchasing/adoption decisions. In the example of the electricity meter, respondents were presented with the four electricity meter designs at the same time and were asked, "Imagine you were selecting an electricity meter for your apartment. Which one of the designs would you prefer the most?" If the product was not something individuals would purchase for themselves, they were asked to think about the product they would select for their community (e.g. their university). Based on consumer preference theory, one would choose the design that was the most desirable, all things considered [163]. Again, optional comment areas were provided for respondents to elaborate on their responses.

Survey Distribution and Quality Control

The survey link was sent with a recruiting email to campus housing email lists, departmental email lists, course email lists, and relevant student clubs' email lists. Students voluntarily

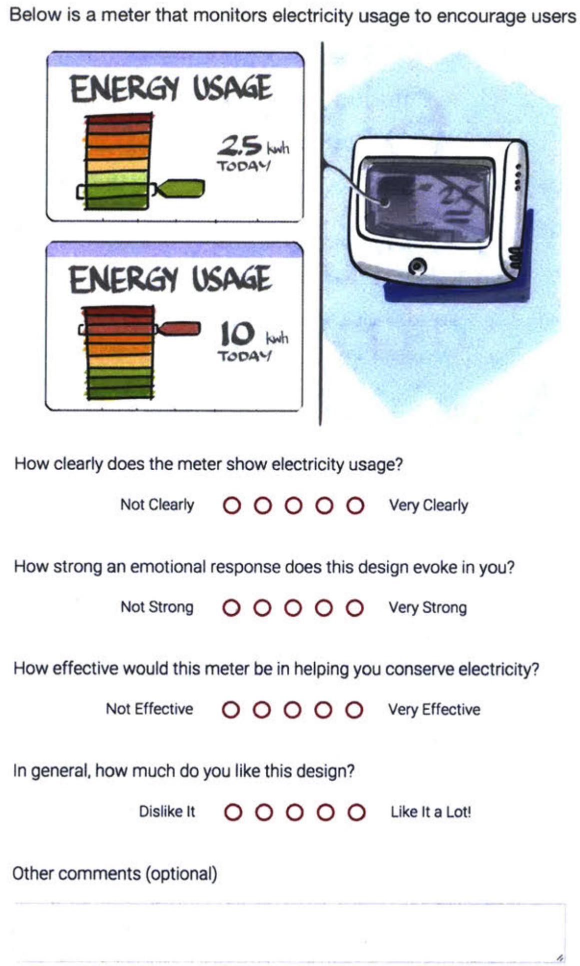


Figure 4-6: Examples of design evaluation questions

took the survey. US participants were provided with the chance to be entered in a lottery for Amazon gift cards of $10, $20 to $50. The entrance into the lottery was independent from the survey responses, and thus we believe no bias was induced with the incentive. No incentives were provided to the Saudi Arabian participants.

The following screening rules were applied to ensure data quality:

- Respondents had to spend at least 5 minutes completing the survey. This minimum time was selected because it was the fastest time the researchers themselves could complete the survey while reading all questions and providing meaningful responses [134, 135].
- Respondents with resource consumption knowledge scores beyond 1.5 interquartile ranges below the first quartile were considered outliers and were excluded from further analysis. This rule was enacted after observing illogical responses to knowledge

questions, such as using the default starting points of the slider bars as answers to all questions.

4.3.3 Data Analysis

Resource Consumption Knowledge Score and Environmental Awareness Score

For the Material usage questions, respondents received 1 point each time they chose the correct way of disposing of a particular type of waste, with a maximum possible score of 10 points. For the Electricity, Transportation, and Water surveys, the score for each respondent's knowledge level of resource usage was calculated using the proposed equation:

$$\text{Knowledge Score}_i = 10 - \sum_{k=1}^{K}[log(E_{ik}) - log(S_k)] \tag{4.1}$$

E_{ik} is the respondent i's answer for question k. K is the total number of questions, varying from four to six for different versions of survey. Each question is weighted equally. S_k is the standard (correct) answer for questions k. The difference between the logarithms of these two values was calculated. Logarithms allow the measurement of the difference in magnitude between two values rather than arriving at an exact number. The log differences for all questions were summed together and subtracted from 10. This subtraction provided a positive knowledge score that represented the resource usage estimation accuracy. The larger the accumulated differences between estimates and standard answers, the lower the knowledge score; the closer the estimations to the standard answers, the higher the knowledge scores. The knowledge scores of different resource categories should not be compared to each other.

Each answer in the environmental awareness questionnaire was coded from 1-5, with responses indicating the most positive attitude towards the environment receiving a score of 5 and the most negative attitude a score of 1. Scores for the eight questions were added together to form a single "Awareness Score", varying from a minimum of 8 to a maximum of 40. The higher the score, the more environmentally aware the respondent was assumed to be.

Median knowledge scores of each resource category were used to split respondents into a "higher knowledge" group and a "lower knowledge" group. Similarly, median awareness scores were used to split respondents into "higher awareness" and "lower awareness" groups.

Design Choice Modeling

Conditional logistic regression models were constructed to determine whether there were any relationships between design ratings and the respondents' choices of most preferred designs [136, 164]. The probability that the i^{th} design being chosen among the four designs of any product was:

$$P_i = \frac{exp(\beta \cdot X_i)}{\sum_{j=1}^{4} exp(\beta \cdot X_j)}, i = 1, 2, 3, 4 \tag{4.2}$$

where X_i was a vector of averaged ratings of the evaluation criteria for design i, and β was a vector of model coefficients. No intercept was included in the model for two reasons: first, design ratings were confounded with forms of design (*text or chart* designs on average had higher clarity ratings, and *metaphor using living creatures* designs in general had higher emotion ratings), thus estimating intercepts would cause the problem of collinearity; and second, each set of four designs was presented in random order, eliminating potential bias introduced by the presentation sequence.

Choice data from the four resource categories were pooled to construct the models. Ratings were normalized to range from 0-1 before fitting to the model so that the model coefficients could be used directly to compare the importance of the explanatory variables. R package *mlogit* [165] was utilized to estimate the model with maximum likelihood method.

Investigating the Influence of Respondents' Demographic Background

This study also noted how the demographic factors of the survey respondents might be related to their resource consumption knowledge, environmental awareness, and choices of designs. Because virtually all respondents were university students around similar age, analysis focused on the potential influence of country (US or Saudi Arabia) and gender of the survey respondents.

To understand the impact of the quantitative and the emotional aspects of a design on the selection of most preferred designs in different respondent groups, logistic regression models were fitted to the following groups respectively: female and male, higher and lower resource consumption knowledge groups, and higher and lower environmental awareness groups. To compare preferences between different groups of respondents, a two-tailed Z-test was used with a large sample assumption to compare the coefficients of different models [166, 167]:

$$Z = \frac{|\beta_1 - \beta_2|}{\sqrt{(SE\beta_1^2 + SE\beta_2^2)}} \tag{4.3}$$

where β_1 and β_2 were the corresponding coefficients from model 1 and model 2 respectively, and the $SE\beta_1$ and $SE\beta_2$ were their standard errors. A significance level of 0.05 was selected. The two-tailed p-values were calculated as:

$$p = 2 \times [1 - \Phi(Z)] \tag{4.4}$$

where $\Phi(Z)$ is the cumulated normal distribution function of Z.

4.4 Results

4.4.1 Study Participants

The survey was distributed among undergraduate and graduate students at one US co-educational technology institute, one US women's liberal arts college, one all-male Saudi Arabian technology university, and two all-female Saudi Arabian universities. In total, 1018 surveys were initiated of which 658 were completed, corresponding to a 65% completion rate. After applying two screening rules, 619 valid responses (94% of completed responses) remained. Table 4.1 summarizes the country and gender distribution of the valid responses.

Table 4.1: Summary of valid survey responses

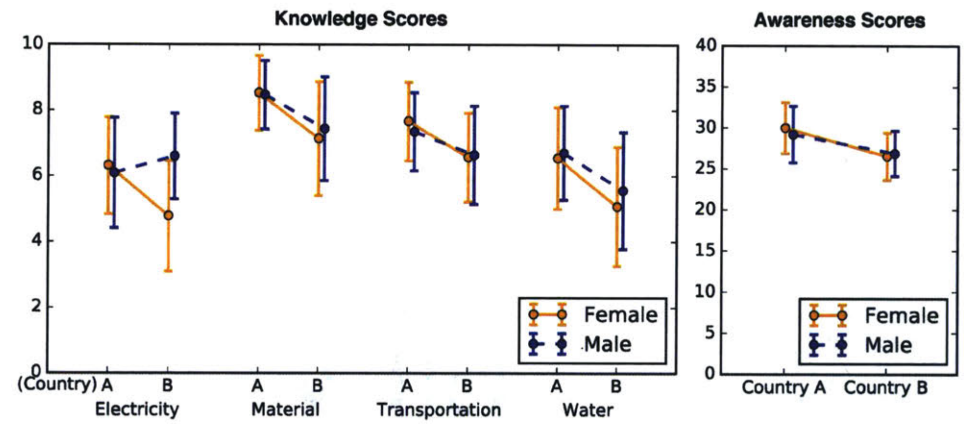
	Electricity	Material	Transportation	Water	Total
Country A	81 (F:60, M:21)	111 (F:77, M:32, S:2)	80 (F:51, M:27, S:2)	99 (F:73, M:26)	371 (F:261, M:106, S:4)
Country B	61 (F:25, M:36)	60 (F:28 M:32)	62 (F:29, M:33)	65 (F:24, M:41)	248 (F:106, M:142)
Total	142 (F:85, M:57)	171 (F:105, M:64, S:2)	142 (F:80, M:60, S:2)	164 (F:97, M:67)	619 (F:367, M:248, S:4)

Note: F - female, M - male, S - self-identified gender.

The sample sizes in US and Saudi Arabia provided 5% and 6% margin of error, respectively, with 95% confidence level for enrolled university students in the two countries. The respondents formed a convenience sample that consisted of students from freshman to PhD, and various departments including science, engineering, social science, and arts. Therefore, we believe our sample was representative of students at the universities that were surveyed. The proportion of female and male students were imbalanced, constrained by gender distributions of the surveyed university populations. However, sufficient data were collected in each group (the smallest group had 21 respondents), which allowed meaningful statistical comparison. The US respondents were allowed to provide their gender information as "self-identified", to align with recent gender identification efforts at some US university campuses. However, very few respondents reported "self-identified" gender, providing low power in statistical inference. Therefore, that data were not included in some of the analysis as noted below.

4.4.2 Resource Consumption Knowledge Scores and Environmental Awareness Scores

The means and the standard deviations of the knowledge scores for each resource category as well as the environmental awareness scores were calculated for each group of respondents of the same gender and country (see Figure 4-7). Higher knowledge scores represent higher ability to estimate resource consumption. Higher awareness scores indicate higher environmental awareness. The data from the self-identified gender group were few and thus were not included.



Two-way ANOVA	F-value (p-value)					DOF
Country	5.944 (0.016*)	31.320 (<0.001***)	16.779 (<0.001***)	22.124 (<0.001***)	126.041 (<0.001***)	1
Gender	7.826 (0.006**)	0.132 (0.717)	0.406 (0.525)	1.141 (0.287)	1.420 (0.234)	1
Interaction	14.029 (<0.001***)	0.652 (0.421)	0.722 (0.397)	0.357 (0.551)	4.598 (0.032*)	1

Figure 4-7: Distributions of knowledge scores and awareness scores

Note: The dots and the error bars represent the average scores and the standard deviation of scores from each group of respondents of same gender and country.

Two-way ANOVA (analysis of variance) was conducted to compare knowledge and awareness scores between countries and genders. The results are also summarized in Figure 4-7. No significant differences were detected between female and male respondents for knowledge scores in Material, Transportation, and Water category. However, respondents from country A had consistently higher knowledge scores for these three categories across both genders. The Electricity category was an exception: country B male respondents had significantly higher knowledge scores compared to country B female respondents regarding the electricity consumption. For the awareness scores, the interaction effect between country and gender was statistically significant at a 0.05 level. However, the effect of country was much more significant, indicating that the main difference in awareness scores was between countries rather than between genders. Overall, the differences in resource usage knowledge and environmental awareness scores was much more significant between the two countries, while gender had small or no significant differences regarding these two scores.

4.4.3 Design Ratings

As expected, large variances of design evaluation ratings were observed and thus we calculated the average ratings for further analysis. The average clarity ratings and emotion ratings of each design are plotted in Figure 4-8. As expected, more quantitative designs featuring *text or chart* had high clarity ratings but relatively low emotion ratings, presumably because they presented concise but dry information on resource usage. In contrast, designs featuring *metaphor using living creatures* had high emotion ratings but relatively low clarity ratings, possibly because the images of animals and plants were evocative but lacked precision in presenting resource usage information. Designs with *visual emphasis* fell between of these two, with relatively high ratings for both clarity and emotion. Designs created by *metaphor using objects* lie on the bottom left side of the figure, with relatively lower ratings on both aspects. Means and standard deviations of all four ratings of each design are summarized in Appendix C.3.

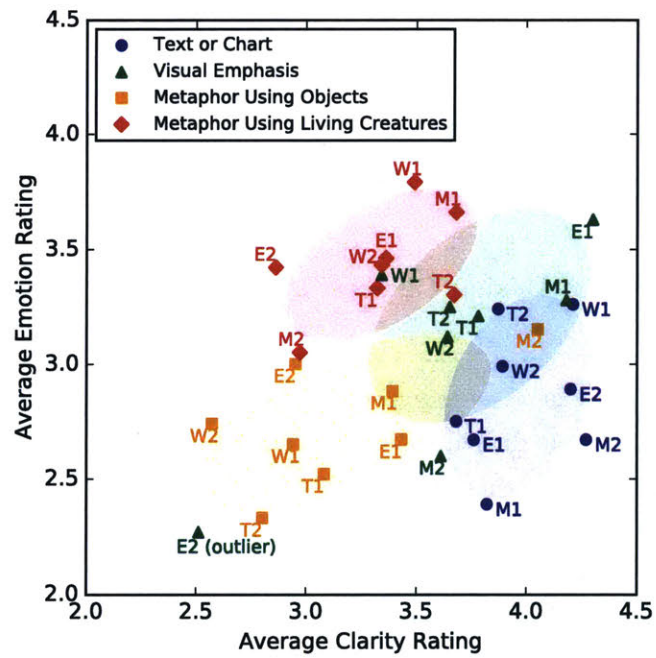


Figure 4-8: Average clarity and emotion ratings of the designs

Note: One point in the figure represents one design; a shaded ellipse represents the mean and covariance of the average ratings of all products generated in one design form; the notation of E1, E2 and etc. correspond to the designs as numbered in Figure 4-1 to Figure 4-4.

Moreover, large variances of the average ratings also existed among products of the same form. Taking the electricity meter (E1) designs and the washing machine (W2) designs as examples, these two products in form of *visual emphasis* had noticeable differences in both clarity emotion ratings, presumably because the electricity meter design had many more visual elements, including a number representing accumulated electricity usage, a colored scale and an indicator of current usage, while the washing machine design only had colored buttons. In the scope of the current study, it would be hard to distinguish users' responses to the different visual elements on a single design.

Pearson correlation coefficients between the average ratings are summarized in Table 4.2. Effectiveness ratings were statistically significantly correlated with both clarity and emotion ratings; appeal ratings were also significantly correlated with clarity and emotion ratings. In addition, effectiveness and appeal ratings were highly correlated with each other. These results indicate that designs that presented more quantitative information and evoked stronger emotions were more likely to be perceived as effective in encouraging resource conservation behavior as well as be appealing to users.

Table 4.2: Pearson correlation coefficients (p-values) between average design ratings

	Clarity	Emotion	Effectiveness	Appeal
Clarity	1	0.310 (0.085)	0.733 (<0.001***)	0.769 (<0.001***)
Emotion	-	1	0.634 (<0.001***)	0.715 (<0.001***)
Effectiveness	-	-	1	0.921 (<0.001***)
Appeal	-	-	-	1

Note: *p<0.05, **p<0.01, ***p<0.001.

4.4.4 Most Preferred Design Choices

Overall, designs featuring *visual emphasis* were voted by highest percentage of participants as "most preferred", followed by designs featuring *text or chart* and *metaphors using living creatures.* Figure 4-9 presents three designs that were voted as the "most preferred" by the majority or plurality of respondents. From left to right they are: an electricity meter design (E1) featuring *visual emphasis*, a paper towel dispenser design (M1) featuring *metaphor using living creature*, and a waste cans design (M2) featuring *text or chart.* They either had a high clarity rating (the waste cans) or high emotion rating (the paper towel dispenser), or both (the electricity meter). Figure 4-8 can be referred to for the clarity and emotion ratings of these designs.

In the open ended comments section of the survey, some reported that they chose their most preferred design because it was "the most emotionally powerful", "the most evocative,

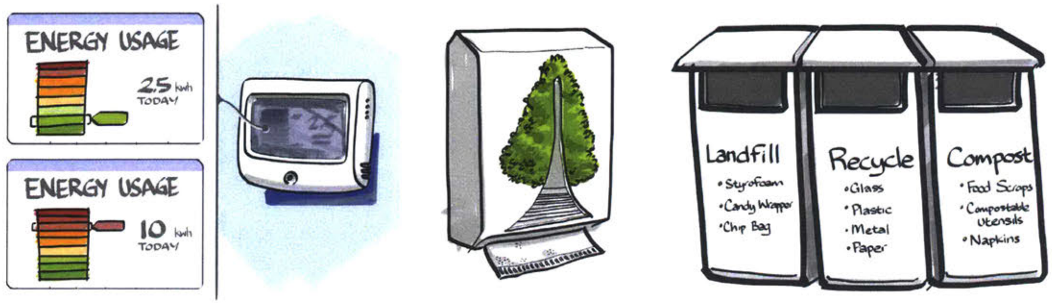


Figure 4-9: Example designs winning majority or plurality votes as the most preferred

and has the strongest emotional response"; while the others preferred to see more data and detailed information: "it's a lot clearer than the other", "it is the most informative and straightforward", "considering resources (consumption) should be rational and practical, not emotional".

Logistic regression model as described in equation 4.2 was used to capture the relationship between the respondents' choices and the average ratings of evaluation criteria for each design. As similar trends were observed across the four resource categories, and creating choice models within each specific category would significantly reduce the sample sizes and consequently reduce the statistical power of the analysis, choice data from all participants (in total N = 1238 choices, two choices per respondent) were pooled to fit this model.

The average clarity and emotion ratings were included in the same choice models as explanatory variables. The effectiveness and appeal ratings were highly correlated with the clarity as well as with the emotion ratings as described in section 4.4.3, and thus were excluded from this model to avoid collinearity. The coefficient for clarity was 1.72 ± 0.13 (t-value = 13.69, p-value < 0.001) and the coefficient for emotion was 1.30 ± 0.14 (t-value = 9.18, p-value < 0.001), both of which positive and statistically significant at a 0.05 level (model log-likelihood = -1541.6). This confirmed that quantitative resource consumption information and emotional evocativeness both played important roles in influencing respondents' choices of their most preferred designs.

When the average effectiveness and the average appeal ratings were included in choice models on their own, their model coefficients were 3.15 ± 0.17 (t-value = 18.83, p-value $<$ 0.001) and 2.69 ± 0.14 (t-value = 18.84, p-value < 0.001), respectively, and their model log-likelihoods were -1499.3 and -1505, respectively. Again, these coefficients were positive and statistically significant at a 0.05 level, showing the "most preferred" design choices also tended to be those rated as effective in encouraging sustainable behavior and overall more appealing.

4.4.5 Comparing Preferred Design Choices between Groups

This analysis focused on comparing respondents' reaction towards the quantitative and emotional aspects of the designs, and thus only included average clarity and emotion ratings as explanatory variables when comparing preferences between demographic groups. To eliminate potential confounding effects between knowledge scores, awareness scores and countries (country A respondents had, on average, higher knowledge scores and higher awareness scores compared to country B, as discussed in section 4.4.2), logistic regression models were fitted to the higher and lower knowledge/awareness groups within each country. Higher and lower knowledge/awareness groups were constructed within each country using the median scores of that country. The preference models of females and males were also compared within each country to eliminate the potential bias induced by unbalanced sample sizes of different gender and country groups. Choice data for electricity-related products from Country B were excluded from the models to eliminate confounding between gender and knowledge scores. Comparisons of the model coefficients are summarized in Figure 4-10.

In both country A and country B, females had significantly higher emotion coefficients compared to males, while there were no significant differences between their clarity coefficients. Again in both countries, the higher knowledge groups (top 50% knowledge scores) had significantly higher clarity coefficients, but not very different emotion coefficients, compared to the lower knowledge groups (bottom 50% knowledge scores). Both clarity and emotion coefficients were not statistically different between the high awareness groups (top 50% awareness scores) and the lower awareness groups (bottom 50% awareness scores). Because country was confounded with knowledge score and gender, direct comparison of coefficients of choice models fitted to each of the two countries were not conducted.

The differences between choice models of females and males suggested that the emotional aspect of a design had much more influence on female respondents' choices of most preferred designs than on male respondents. The quantitative aspect of a design appeared to be much more important to respondents who had higher resource consumption knowledge scores, indicating that respondents who were better at estimating resource consumption or possessed more knowledge about resource consumption were more engaged with the quantitative resource usage data provided by the eco-feedback designs.

4.5 Discussion

Key findings regarding the original research questions are highlighted and discussed below, as well as the study limitations:

Q1: How are quantitative and emotionally evocative usage information presented in an

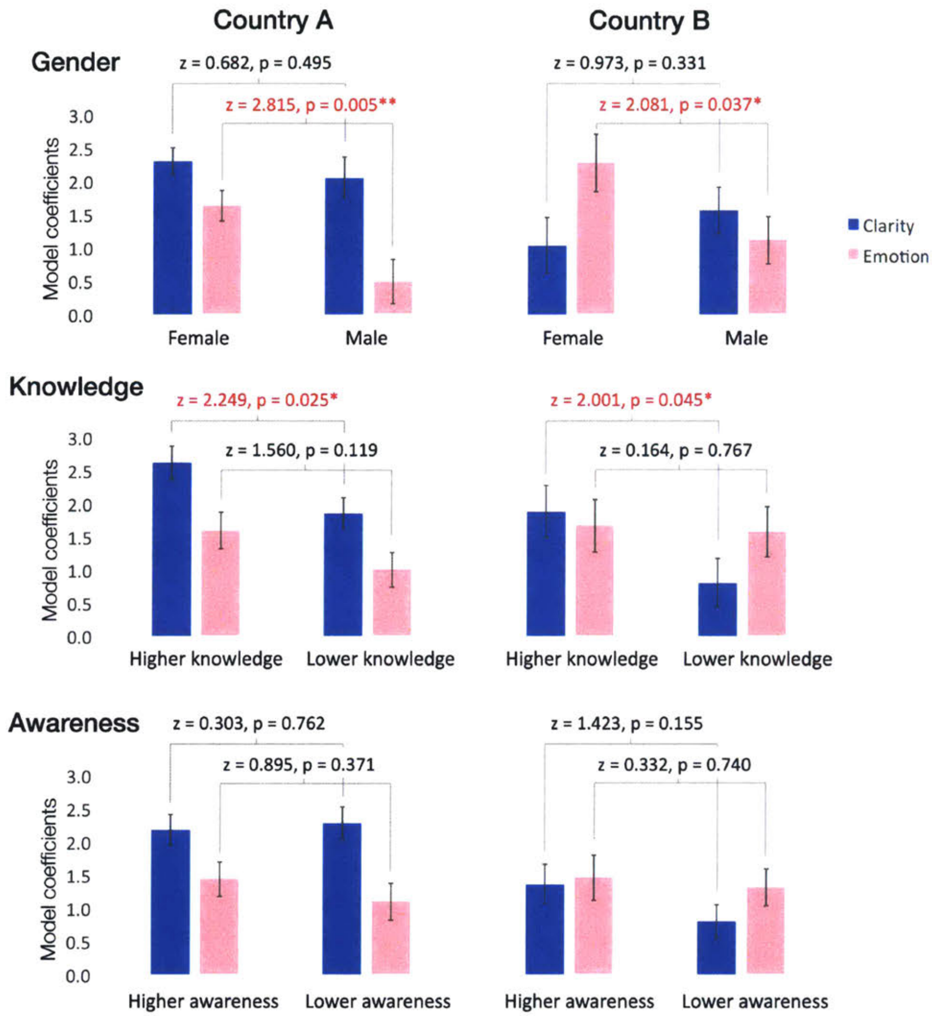


Figure 4-10: Comparison of logistic regression model coefficients
Note: Blue bars and pink bars represent the estimated model coefficients of clarity ratings and emotion ratings respectively. Error bars represent the standard errors of coefficients. Z statistics and p values are calculated according to equations 4.3 and 4.4. *$p<0.05$, **$p<0.01$.

eco-feedback product linked to users' perceptions of the appeal of the overall design and its effectiveness in encouraging sustainable behavior?

Traditional theoretical frameworks such as theory of reasoned action, theory of planned behavior and value-belief-norm theory [168, 169] were developed to predict pro-environmental behavior with people's environmental knowledge and attitude. In addition, numerous empirical studies have explored the links between attitude, knowledge and behavior [170, 171]. Only recently have the impact of emotions on motivating sustainable behavior and moderating environmental belief and attitude gained attention [68, 70, 71]. Our study took a product-design perspective and investigated the presentation of resource usage information on products, with the emphasis not only on quantitative feedback, but also on the emotional evocativeness of the information presentation.

The results demonstrated that both quantitative resource usage information and emotional power of a design were important to the success of eco-feedback products that we evaluated, in the sense that designs with higher clarity ratings and higher emotion ratings tended to be rated as more appealing, more effective in encouraging sustainable behavior, and were more frequently chosen as the most preferred. This study did not examine the emotional valence or the specific type of emotions that were evoked by the designs. Different emotions may have different influence on user perception and preference [172]. While positive emotions (such as satisfaction) could encourage users to be more involved with environmental sustainable practices, negative emotions such as guilt might drive users away from further engagement with eco-feedback products [173]. The next chapter will discuss in detail the types of emotions evoked by a design and their links to the effectiveness in encouraging pro-environmental behaviors.

In addition, the effectiveness and appeal ratings for designs were highly correlated. It may be that users were more attracted to designs they believed could spark environmentally-conscious behaviors; on the other hand, it is well known that designs that are more visually attractive are generally perceived to be more effective and work better [174, 175], regardless of whether they actually are. One limitation of this study is that the results were immediate user evaluations of designs. It the future, it would be interesting to monitor longer-term user-product interactions and investigating the eco-feedback products' effectiveness in encouraging sustainable behavior change, establishing habits, and potential changing values and beliefs concerning the environment.

Q2: Do users with different levels of environmental awareness or quantitative resource consumption knowledge, or with different demographic background respond differently to the quantitative and emotional aspects of resource usage information presented in an eco-feedback product?

The quantitative and the emotional aspects of resource usage information can influence users' thinking process, but in different ways. Quantitative usage might prompt users to think about their consumption in an logical and active manner known as system 2 thinking [176], and thus whether a user responds to it could largely depend on their ability to properly interpret the information (environmental knowledge) and their willingness to take the effort to interpret the information (environmental awareness). Not surprising, significant evidence was found that respondents with higher resource consumption knowledge scores were much more sensitive to the quantitative aspect of a design compared to respondents whose knowledge scores were lower. This illustrates a limitation of presenting merely quantitative resource usage information: to users who know little about resource consumption, the quantitative data might not be very attractive or informative, let alone encourage sustainable behaviors, just as calorie labeling of food does little for those who lack the understanding of calorie information [177, 178].

The emotional aspect, on the contrary, might prompt users to react in a faster and automatic manner (system 1 thinking). It was found that respondents were sensitive to the emotional aspect of designs to a similar degree, regardless of their resource consumption knowledge scores. This finding is useful as it provides guideline to enlarge the impact of eco-feedback products by emotionally engaging a broader audience of users, including those who don't possess much quantitative knowledge about resource consumption. In addition, female respondents were found to be more sensitive to the emotional aspects of the design than male respondents, consistent with empirical evidence that women generally response more emotionally to visual stimulus than men [179]. This finding can help form principles for designing compelling eco-feedback products for specific genders.

Contrary to our expectation, no significant difference in design preferences was found between respondents with higher or lower environmental awareness scores. The environmental awareness evaluation questions in this study were built upon existing measures of pro-environmental attitude [159, 160]. However, self-reported environmental awareness can be subjective, and validations of the measurements should be conducted in future work.

We believe the four categories (Electricity, Material, Transportation, and Water) explored in the study covered a large enough range of resources and environment-related fields to provide generalizable results. Nonetheless, the eco-feedback strategy could be applied to other categories, such as encouraging a low-carbon diet [180] or reducing food waste [181].

Four forms of designs were investigated in this study. *Visual emphasis* was shown to be an effective form of design for the eco-feedback products in this study. On average, these types of designs had the highest ratings on both clarity and emotion and tended to receive more votes as the most preferred designs. Meanwhile, *text or chart* and *metaphor using living creatures* were demonstrated to be the most quantitative and the most emotionally evocative design forms, respectively. However, it should be noted that the forms of design were intentionally isolated in this study so that their influence could be examined individually. In practice, designers are not obligated to follow a single form of design, but adjust, combine them, or create new ones as needed. In addition, there are other forms of design and ways of presenting resource usage information that are worthy of study, for example, setting goals for resource conservation [182] or gamifying the resource conservation process [183].

4.6 Conclusion

This chapter focused on a strategy of eco-feedback that explicitly presents resource consumption information to encourage sustainable behavior. It contributed to the rich literature of cleaner production by presenting an experimental, evidence-based approach for user-centered eco-design that identifies opportunities to reduce residential resource consumption by influencing the daily product-use behavior of people. The stance of the work was consistent with other research in cleaner production of investigating the social and psychological aspects of eco-design implementation [173, 184], and bridged the gap between the technical aspects of eco-design development [185] and interventions for promoting resource conservation behavior [186].

In this study, we evaluated how users perceive thirty-two eco-feedback designs of household products in four categories, including Electricity, Materials, Transportation, and Water. We surveyed potential users across a wide geographical area for their responses by presenting them with sketches of the designs. We mapped the designs to a 2D space of quantitative and emotional, and demonstrated that both the quantitative and emotional power of a design were important to the success of eco-feedback products in the sense that designs rated to show clearer resource usage information and evoke stronger emotions tended to be rated as more appealing, more effective in encouraging sustainable behavior, and are more frequently chosen as respondents' most preferred designs. It was found that presenting quantitative resource usage information was more helpful to respondents who could better estimate resource consumption, while the emotional evocativeness of a design aided respondents with lower and higher resource consumption knowledge to a similar degree. In addition, we found that images of living creatures and strong visual cues evoked strong emotions in users, and female participants in general responded more strongly than male to this emotional evocativeness.

These findings challenge the traditional strategies of designing eco-feedback products whose single focus was on presenting quantitative information, and point to the direction of creating designs that can better engage users emotionally. The four specific forms of design investigated in the study have implications for ways of designing and developing eco-feedback products in practice. In addition, the methods established in this study that collect user feedback on provisional design representations of eco-feedback products could be used by designers to accelerate the development of all kinds of sustainable products.

Chapter 5

Investigating User Emotional Responses to Eco-Feedback Designs

5.1 Motivation

In the last chapter, we investigated eco-feedback products in a range of styles, from more quantitative (e.g. displaying the power consumption of an appliance in Watts), to more emotionally evocative (e.g. displaying a wilting sunflower). Results suggested that designs which were both quantitatively clear and emotionally evocative were also the most appealing. However, it was not clear which particular user emotions were evoked by these designs, or what roles different emotions might play in influencing user behavior.

Existing studies that explore these questions were also rare. Dillahunt, et al. [187] designed an interactive virtual polar bear as a motivator for conserving energy. It was found that people who were more emotionally attached to the polar bear exhibited greater concern for the environment. However, there is little understanding of what precisely users would describe themselves as feeling in the context of using such product. In addition, there were few guidelines on how to design products to elicit strong and appropriate emotions in order to encourage sustainable behavior.

To fill this gap, this current chapter strives to better understand specific user emotions associated with eco-feedback designs and to investigate how they are linked to users' perception of the designs and their behavior change. Three main questions explored in this chapter are:

Q1: What are the emotions that arise from users' interactions with eco-feedback products?

We are interested in identifying a spectrum of emotions that builds on validated emotion assessment frameworks including the Positive and Negative Affect Schedule [188] and the Consumption Emotion Set [189]. Some expected emotions include interest, satisfaction, worry and guilt. We anticipate that the emotions will largely depend on the specific product usage scenario.

Q2: What role do emotions play in influencing users' sustainable behavior and their perceptions of eco-feedback products?

We seek to understand how a user's emotions influence their behavior with respect to conserving resources. We want to evaluate whether emotionally rich eco-feedback products can better promote sustainable behavior, and identify the specific emotions that are most effective in encouraging behavior change. We will also investigate how different emotions can impact users' perceptions of eco-feedback designs.

Q3: How can we design eco-feedback products to evoke strong and appropriate emotions in users to encourage sustainable behavior?

In the study described in the last chapter, quantitative and figurative design representations were compared on the strength of emotional responses they evoked in users. In this work, these categories of eco-feedback design were further evaluated. We expected that designs using figurative metaphors (such as animals) as reminders of environmental sustainability would be more emotionally evocative than designs showing strictly quantitative information (such as the total amount of resources consumed).

To address these questions, an in-lab experiment was conducted with 68 participants of varying backgrounds. Participants evaluated design concepts for four eco-feedback products and reported how they would feel and behave while using these products.

5.2 Related Work

5.2.1 Measuring Users' Emotions

The prevailing method to measure human emotions is self-reporting. The Positive and Negative Affect Schedule (PANAS) is a tool that measures the intensity of both positive and negative affect of a person [188]. It contains two ten-item scales, ten verbal descriptors of positive emotion such as Excited or Proud, and ten verbal descriptors of negative emotion such as Afraid or Irritable. Along these lines, Richins investigated a set of 175 emotion words that are specifically related to a consumer's consumption experience [189]. He further narrowed the list down to a Consumption Emotion Set (the CES), which contains the most representative 34 emotion descriptors. Another popular instrument to measure emotions is the Self-Assessment Manikin (SAM), which uses non-verbal pictorial assessment to measure the pleasure, strength, and dominance that are associated with a person's emotions [190]. Similarly, Desmet developed the Product Emotion Measurement Instrument (PrEmo), which is a set of cartoon figures that help users to express emotions related to owning or using a product [191]. These methods are easy to implement, and a well-designed self-reporting scale can be valid and reliable [192].

Another way to assess emotions that is gaining in popularity is measuring physiological responses of the human body, a group of methods enabled by the rapid growth of sensing technology [193]. Some common practices include observing facial expression [194] or vocal cues [195], measuring heart rate, skin conductivity or respiration [196], and detecting brain activities using electroencephalogram (EEG) [197] or functional magnetic resonance imaging (fMRI) [198]. These methods are considered more objective compared to self-reporting methods. However, their implementations are usually more complex and expensive, and the gathered data are usually more open to interpretation.

To gauge user emotions, design researchers have asked people to recall their emotional experience with products [199] or used a diary method to track emotions over the course of using a product [200]. To collect feedback on provisional product ideas, design representations such as line drawings [201] or prototypes [202] have been used to elicit user emotions. Scenario-based design is an approach that captures the essence of a product's use by creating a story or context for the experience [203]. It has been used to gather feedback on the experience of using a product in the early design stage [204].

5.3 Methods

Overview: Four eco-feedback products were created for this experiment to encourage electricity or water conservation behavior in users. Two versions of each product were sketched by a professional industrial designer. In-lab experiments were conducted with participants of diverse demographics and backgrounds. The participants evaluated the designs and reported how they would feel and behave if they were using these products. Detailed usage scenarios were described to the participants to help reveal more realistic emotions.

5.3.1 Design Prompts

The four products meant to encourage electricity or water conservation investigated in the previous chapter were further investigated here. They were:

- An **Electricity Meter** that monitors home electricity usage
- A **Light Switch** that reminds people to turn off the lights when leaving a room

- A **Water Faucet** that monitors the day's cumulative water usage
- A **Washing Machine** with a selectable water-saving mode

Two versions of each product were created: a *Quantitative* design that displayed the resource consumption information in the form of text or a chart, and a *Figurative* design that used a drawing of an animal as a reminder of the impact of a product's resource usage on environmental sustainability. These designs were built upon the *text of chart* designs and the *metaphor with living creature* designs in the previous chapter, and were modified to make the intention of encouraging resource conservation behavior clearer. For example, a target usage value was added to the electricity meter display to set a goal for electricity conservation.

In addition, a *Neutral* design was created for each product, with either no specific instruction on resource conservation (the electricity meter) or no feedback information on resource consumption at all (the light switch, water faucet and washing machine designs). These neutral designs served as a baseline control group for user emotions and actions. Figure 5-1 presents the sketches of each version of the four eco-feedback products.

Simple GIF animations were created for the electricity meter and water faucet designs to show the information products would display during use. For example, GIF animations of the water faucet designs showed water flowing out of the faucet as the number of liters of water used ticked up; in the meantime, the quantitative water faucet design showed the bar chart growing and the figurative water faucet design showed the water level in the fish tank dropping.

5.3.2 Usage Scenarios

For each product, users were presented with an actionable scenario in which they could take immediate actions to conserve electricity or water. The scenarios were constructed such that there was a tradeoff of convenience for the sustainable action. For example, when evaluating the water faucet designs, participants were asked to imagine that they were washing dishes after dinner; they started to soap the dishes after rinsing them, and noticed the water usage increasing on the faucet display. They were asked how likely they were to take actions to conserve resources, for example, turning off the faucet. A 1-7 scale was provided where 1 was "definitely not" and 7 was "definitely" taking action. The responses to this question will be referred to as the "certainty of taking immediate resource conservation action" or "certainty of resource conservation action" for short in the rest of this paper. The scenarios were presented in neutral language in order to reduce social desirability bias that might incline participants to respond that they would always take the sustainable action [205].

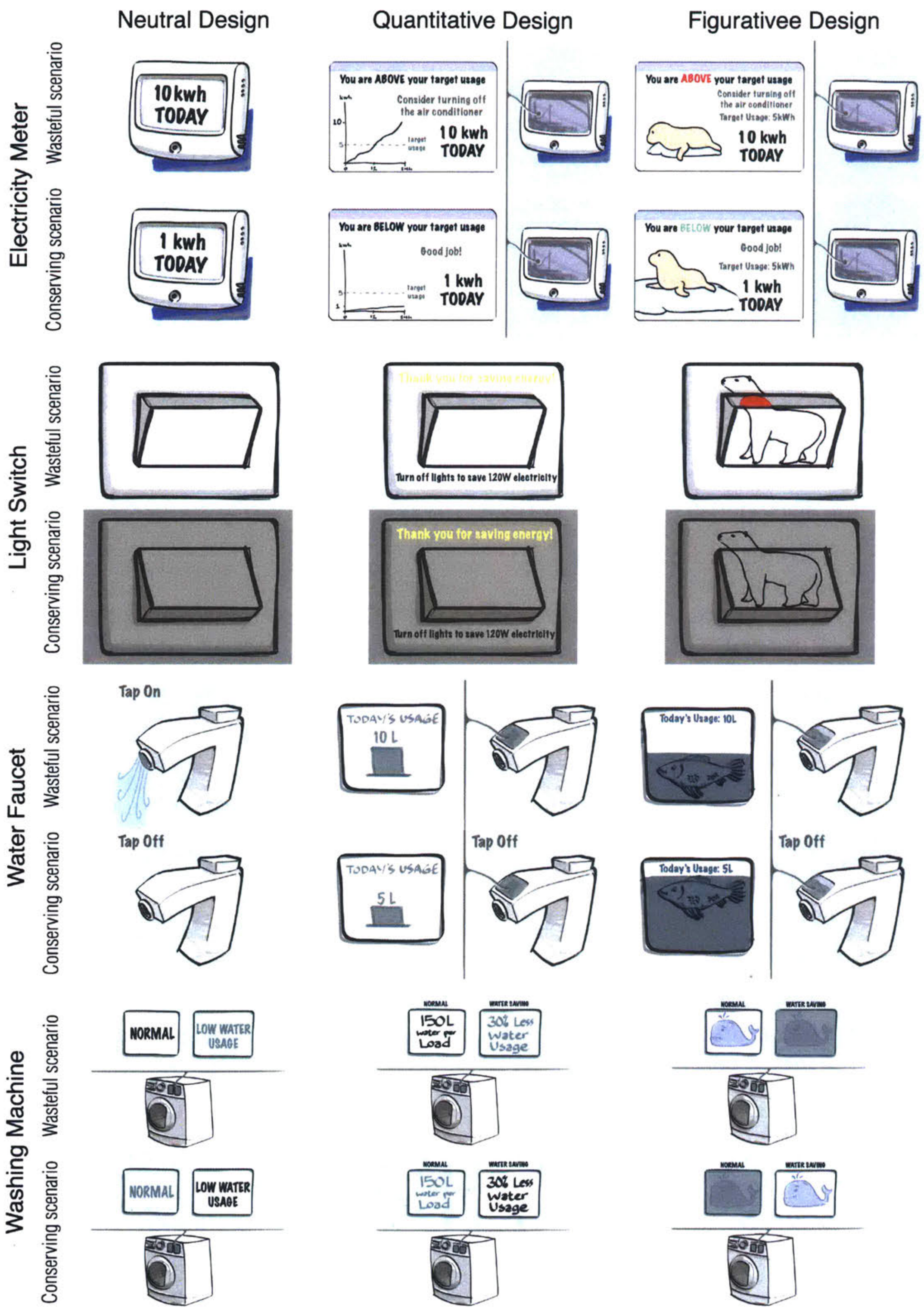


Figure 5-1: The neutral, quantitative and figurative designs of four eco-feedback products in a conserving scenario and a wasteful scenario

Additionally, a conserving and a wasteful scenario was created for each product. In the conserving scenario, participants were asked to imagine that they used the product sustainably or followed the directives of the product to conserve resources. In the wasteful scenario, participants were asked to imagine that they failed to use the product sustainably, thus wasting water or electricity. In the water faucet example, the user in the conserving scenario would "turn off the faucet while soaping the dishes to save water"; in the wasteful scenario, the user would "let the water run during the whole time". These scenarios were described in written form, and accompanied by sketches of the designs summarized in Figure 5-1. Participants were asked to report their emotions (how they would feel) in both the conserving and the wasteful scenarios.

The actionable scenario and the conserving and wasteful scenarios of the figurative water faucet design, along with the questions asked to the participants, are provided in Appendix D.1 as examples.

5.3.3 Emotion Evaluation

In this study, sketches were used as design representations and scenarios of users interacting with eco-feedback products were created to elicit user emotions. We explored multiple quantitative emotion assessment methods, including self-reporting, skin conductivity measurement and facial expression detection when designing this study. Self-reporting was chosen to measure users' emotions because we found it more meaningfully interpretable and more effective at distinguishing between subtly different emotions in the context of our study, whereas skin conductivity (for example) often measured no noticeable change between different scenarios.

Participants self-reported their emotional reactions in both the conserving and the wasteful scenario with verbal emotion descriptors. Fifteen emotions were evaluated: *interested, excited, proud, joyful, satisfied, hopeful, warmhearted, surprised, upset, worried, annoyed, embarrassed, guilty, skeptical,* and *bored.* These emotion labels were chosen from the PANAS [188] and the CES [189] word sets, and were pilot tested for their appropriateness to the usage scenarios. The emotions were intended to span positive and negative options, and to include words associated with a user's consumption experience and resource conservation behavior. The number of emotions was formulated such that it was sufficient for describing the product usage scenarios but also concise enough to avoid survey fatigue.

Participants reported to what extent they would feel each emotion on a 1-5 scale: 1 - Not at all, 2 - Slightly, 3 - Moderately, 4 - Strongly, and 5 - Extremely. For mathematical convenience, the responses of 1-5 were later mapped to a 0-4 scale, thus the response of "not at all" would correspond to an emotional intensity of 0. Then the emotional responses were normalized using the participants' positive and negative affect, the details of which are described in Results section. The sequence in which the 15 emotions were presented was randomized in the survey.

5.3.4 Experimental Setup

The experiment was conducted on individual participants. Seventy-one adult participants were recruited via the MIT Behavioral Research Lab, a dedicated facility on campus that maintains a pool of potential research participants for campus researchers across the institution. Participants can be of any background and were not limited to students or staff working on campus, and thus their age and level of education could cover a broad range. Each participant received a $15 Amazon gift card as compensation. The Behavioral Research Lab served as the setting for the experiment itself.

Participants were divided into three experimental groups: a control group that viewed only neutral designs, a quantitative group that viewed only quantitative designs and a figurative group that viewed only figurative designs. The experiments were conducted in two stages. Stage 1 took place in February 2018. Thirty participants were recruited and tested with only the quantitative and figurative designs. Stage 2 took place in June 2018 with an additional 41 participants. All three groups of designs were tested in this second stage. Minor adjustments were made to the experimental process between the two stages as described in the next section.

5.3.5 Experimental Process

The entire experiment took about 45 minutes. The main steps of the process were:

a) **Introduction** Participants were introduced to the scope of the study and the process of the experiment. Informed consent was obtained.

b) **Practice Questions** To familiarize participants with the emotion evaluation questions, two practice questions were asked: one reporting their current moods and another reporting emotions in a described scenario. Each question had a short list of five emotion descriptors. Any ambiguity in the questions was clarified at this point.

c) **Pro-Environmental Attitude** Pro-environmental attitudes of the participants were evaluated with the New Ecological Paradigm (NEP) scale [159]. The results were used to check if the participants' product usage behavior was influenced by their environmental awareness.

d) **Current Moods** Participants reported their current positive and negative affect with the PANAS [188], which has ten positive and ten negative emotion descriptors.

The results were used to normalize participant's emotional responses when using the products.

e) **Product-Related Emotions & Design Evaluation** Participants were presented with four eco-feedback products and reported what they would do and how they would feel in usage scenarios as described in section 5.3.2 and section 5.3.3. The sequence in which the four products were presented was randomized, and so was the presentation sequence of the conserving or wasteful scenarios. In addition, the participants evaluated each design on its *Aesthetics*, *Usefulness* for encouraging resource conservation behavior, their *Willingness to Use* it, and its *Overall Quality*. These criteria were created based on selected measures of Garvin's eight dimensions of product quality [84]. Only measures that the participants could reasonably judge by looking at the design sketches were chosen, and they were tailored to the features of the eco-feedback designs. Example questions can be found in Appendix D.1.

f) **Demographics Questions** Data including age, gender, level of education, occupation and household yearly income were collected.

g) **Post-Experimental Interview** Semi-structured interviews were conducted asking open ended questions including how much the participants liked the designs and why; what kind of emotions they would feel when using the products and why; and how they would behave (take actions to conserve resources or not) and why. Notes were taken by researchers during the interviews and were summarized to provide insights into how and when the participants would feel certain emotions, and how emotions were linked to participants' behavior and their evaluations of the designs.

Questions in step c), d), e), and f) were presented in a survey created with Qualtrics, the online survey tool. The participants answered the questions on a computer by themselves. The researchers were out of view to reduce social desirability bias on their responses, though at least one researcher was nearby in case the participant had questions. The entire experiment was video recorded.

Two rounds of pilot studies were conducted. The first was with five students and focused on the wording of the questions, especially the emotion evaluation questions. The second round focused on testing the experimental process and was conducted with three graduate students. The design prompts and the questions were adjusted based on the feedback from each round of pilot studies.

In stage 1 of the experiment, the sequence of the experimental steps was exactly as described above. In stage 2, the sequence was adjusted and step c (pro-environmental attitutde) was moved between step e (product-related emotions & design evaluation) and step f (demographics questions) to avoid any potential priming effect of the pro-environmental attitude questions on participants' responses to the scenarios. This adjustment did not significantly influence the results, as described in the next section.

5.4 Results

5.4.1 Study Participants

Thirty and forty-one participants took part in the study in stages 1 and 2, respectively. Three participants in stage 2 reported noticeably inconsistent emotions in step e (survey) and step g (interview) of the experiment (for example, reporting negative emotions in wasteful scenarios during the interview, however, indicating only positive emotions in wasteful scenarios in the survey). We considered their data unreliable and excluded them from the dataset, leaving 68 participants for further analysis.

Among the 68 participants whose data were kept for further analysis, 37 were female and 31 were male. They varied in age from 21 to 65. The gender and age information was avaialble to the researchers on an on-line registration system of the Behavioral Research Lab prior to the experiments, and was used to evenly assign the participants to the experimental groups within each stage. Twenty-five participants were current college or graduate students; the rest had various occupations including researcher, manager, clinician, preschool teacher, accountant, driver, carpenter, and others. The plurality (32 participants) had a bachelor's degree or equivalent level of education; 14 had some college or lower level of education; and 22 had a master or doctoral degree. Participants with different levels of education were distributed evenly in the experimental groups. The distribution of participants' gender, age and level of education within each experimental group are summarized in Table 5.1.

Table 5.1: Demographic distributions of study participants

	Control Group	**Quantitative Group**	**Figurative Group**
Total number	14	26	28
Gender			
Female	7	14	16
Male	7	12	12
Age			
Mean ± SD	38.4 ± 10.6	38.0 ± 14.1	37.3 ± 15.1
Level of education			
Some college or lower	3	6	5
Bachelor's degree or equivalent	6	11	15
Master or doctor degree	5	9	8

Participants' pro-environmental attitude scores varied from 35 to 75, with 57 as the median (the possible range of the pro-environmental attitude scores was 15 to 75). No significant differences were found between the experimental groups (ANOVA F-value = 0.185, p-value = 0.831)

Stage 1 and stage 2 data were combined together. We did this because no significant differences were observed between the two stages in participants' certainty of taking immediate resource conservation actions or in their pro-environmental attitude scores (detailed analysis see Appendix D.2). This suggested that the adjustment of the experimental sequence didn't make any significant impact on the study results, and asking pro-environmental attitude questions (step c of the experiment) prior to the design evaluation questions (step e of the experiment) didn't induce any significant priming effect.

5.4.2 Emotion Normalization

Participants' initial positive and negative affect, assessed with the PANAS, represented their mood states in the studies. They were measured in step d) of the experiment, before the participants seeing or evaluating the designs. Figure 5-2 summarizes their distributions. No significant differences were found between the experimental groups with ANOVA tests (positive affect F-value = 0.019, p-value = 0.981; negative affect F-value = 0.571, p-value = 0.568).

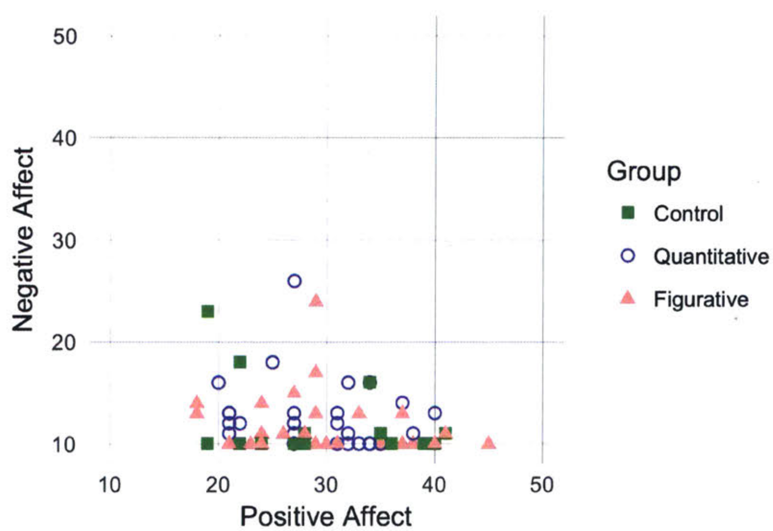


Figure 5-2: Participants' positive and negative affect

Participants' reported emotions about using products were significantly correlated with their positive and negative affect (see Table 5.2). To be specific, positive emotions (*interested, excited, proud, joyful, satisfied, hopeful,* and *warmhearted*) and *surprised* that the participants would feel in both conserving and wasteful usage scenarios were observed to be significantly positively correlated with the positive affect. Negative emotions (*upset, worried, annoyed,* and *skeptical*) were observed to be significantly positively correlated with the negative affect in both conserving and wasteful scenarios; in addition, negative emotions in wasteful scenarios were also significantly positively correlated with the positive affect. Benjamini & Hochberg (BH) method was applied to adjust the p-values to reduce false detection in multiple comparisons.

Table 5.2: Pearson correlations between affects and emotions before normalization

	Positive Affect		Negative Affect	
Emotion	Conserving Scenario	Wasteful Scenario	Conserving Scenario	Wasteful Scenario
Interested	0.391 (<0.001)	0.319 (<0.001)	-0.006 (0.917)	-0.061 (0.600)
Excited	0.333 (<0.001)	0.192 (0.003)	0.012 (0.914)	-0.036 (0.759)
Proud	0.373 (<0.001)	0.197 (0.002)	-0.033 (0.766)	-0.153 (0.038)
Joyful	0.282 (<0.001)	0.201 (0.002)	0.061 (0.600)	-0.145 (0.049)
Satisfied	0.28 (<0.001)	0.149 (0.019)	-0.016 (0.909)	-0.054 (0.615)
Hopeful	0.404 (<0.001)	0.213 (0.001)	-0.020 (0.887)	0.009 (0.914)
Warmhearted	0.264 (<0.001)	0.189 (0.003)	0.057 (0.615)	-0.119 (0.127)
Surprised	0.187 (0.003)	0.214 (0.001)	0.010 (0.914)	-0.029 (0.795)
Upset	0.037 (0.609)	0.256 (<0.001)	0.190 (0.010)	0.190 (0.010)
Worried	-0.038 (0.609)	0.200 (0.002)	0.237 (0.001)	0.185 (0.010)
Annoyed	0.025 (0.734)	0.173 (0.006)	0.158 (0.034)	0.267 (<0.001)
Embarrassed	0.073 (0.274)	0.187 (0.003)	-0.047 (0.655)	0.078 (0.428)
Guilty	0.015 (0.828)	0.163 (0.01)	-0.052 (0.615)	0.139 (0.059)
Skeptical	0 (-0.995)	0.086 (0.198)	0.207 (0.006)	0.184 (0.01)
Bored	0.093 (0.167)	0.178 (0.005)	-0.038 (0.757)	-0.088 (0.337)

Note: The correlation results are reported as *correlation coefficient (p-value)*. BH adjustments were applied to the p-values. Significant correlations on 0.05 levels are highlighted in gray.

Based on these observations, equation 5.1 and equation 5.2 were used to normalize the emotions to rule out the impact of participants' mood on their emotional reactions towards the products:

$$Normalized(PE_i) = \frac{PE_i}{PA_i/max(PA_i)} \tag{5.1}$$

$$Normalized(NE_i) = \frac{NE_i}{\sqrt{(\frac{PA_i}{max(PA_i)})^2 + (\frac{NA_i}{max(NA_i)})^2}} \times \sqrt{2} \tag{5.2}$$

where PE_i were any positive emotions (PE) or the emotion *surprised* of participant i, NE_i were any negative emotions (NE) of participant i; PA_i and NA_i were the positive affect (PA) and negative affect (NA) of participant i; $max(PA_i)$ and $max(NA_i)$ were the largest positive affect and largest negative effect among all participants. The maximum values were included so that the positive emotions and negative emotions would be on comparable scales after normalizations. The normalizations largely reduced the correlations (see Table 5.3).

Table 5.3: Pearson correlations between affects and emotions after normalization

Emotion	Positive Affect		Negative Affect	
	Conserving Scenario	Wasteful Scenario	Conserving Scenario	Wasteful Scenario
Interested	0.094 (0.263)	0.185 (0.056)	0.076 (0.459)	-0.012 (0.898)
Excited	0.132 (0.111)	0.096 (0.263)	0.057 (0.524)	-0.010 (0.900)
Proud	0.085 (0.303)	0.147 (0.104)	0.033 (0.732)	-0.152 (0.134)
Joyful	0.058 (0.487)	0.144 (0.104)	0.127 (0.157)	-0.142 (0.134)
Satisfied	-0.101 (0.263)	0.035 (0.699)	0.060 (0.524)	-0.026 (0.809)
Hopeful	0.175 (0.056)	0.112 (0.197)	0.033 (0.732)	0.058 (0.524)
Warmhearted	0.043 (0.634)	0.140 (0.106)	0.100 (-0.272)	-0.107 (0.254)
Surprised	0.058 (0.487)	0.156 (0.103)	0.059 (0.524)	-0.020 (0.838)
Upset	0.016 (0.789)	0.135 (0.110)	0.138 (0.134)	0.062 (0.524)
Worried	-0.09 (0.278)	0.096 (0.263)	0.157 (0.134)	0.089 (0.326)
Annoyed	-0.019 (0.781)	0.061 (0.487)	0.105 (0.254)	0.140 (0.134)
Embarrassed	0.033 (0.699)	0.064 (0.487)	-0.055 (0.529)	-0.019 (0.838)
Guilty	-0.024 (0.769)	-0.022 (0.774)	-0.059 (0.524)	-0.001 (0.992)
Skeptical	-0.056 (0.488)	0.024 (0.769)	0.134 (0.134)	0.115 (0.222)
Bored	0.060 (0.487)	0.123 (0.143)	-0.045 (0.622)	-0.090 (0.326)

Note: The correlation results are reported as *correlation coefficient (p-value)*. BH adjustments were applied to the p-values. No correlations were significant on 0.05 level.

5.4.3 Spectrum of Emotions

After normalization, the emotional intensity varied in a range between 0-10, where 0 representing not feeling an emotion at all and 10 indicating feeling an extremely strong emotion. Though the intensity of emotions regarding using an eco-feedback product varied across participants and was influenced by the types of products, the trend was consistent that more positive emotions arose in the conserving scenarios and more negative emotions arose in the wasteful scenarios. The overall distributions of user emotions in each experimental group are summarized in Figure 5-3, with motions towards different products pooled together,

Overall (combining three experimental groups), emotions with the highest mean values in the conserving scenarios were *satisfied* (mean $\pm$ sd: 3.3 $\pm$ 1.8), *proud* (2.5 $\pm$ 1.8), and *interested* (2.2 $\pm$ 1.7). The strongest emotion in the wasteful scenarios was *guilty* (2.9 $\pm$ 1.8), followed by *upset* (2.0 $\pm$ 1.6), *embarrassed* (1.9 $\pm$ 1.7), *annoyed* (1.9 $\pm$ 1.7), and *worried* (1.7 $\pm$ 1.5). *Skeptical* (0.6 $\pm$ 1.1) was the dominant negative emotion in conserving scenarios; and *interested* (1.2 $\pm$ 1.5) was the dominant positive emotion in wasteful scenarios.

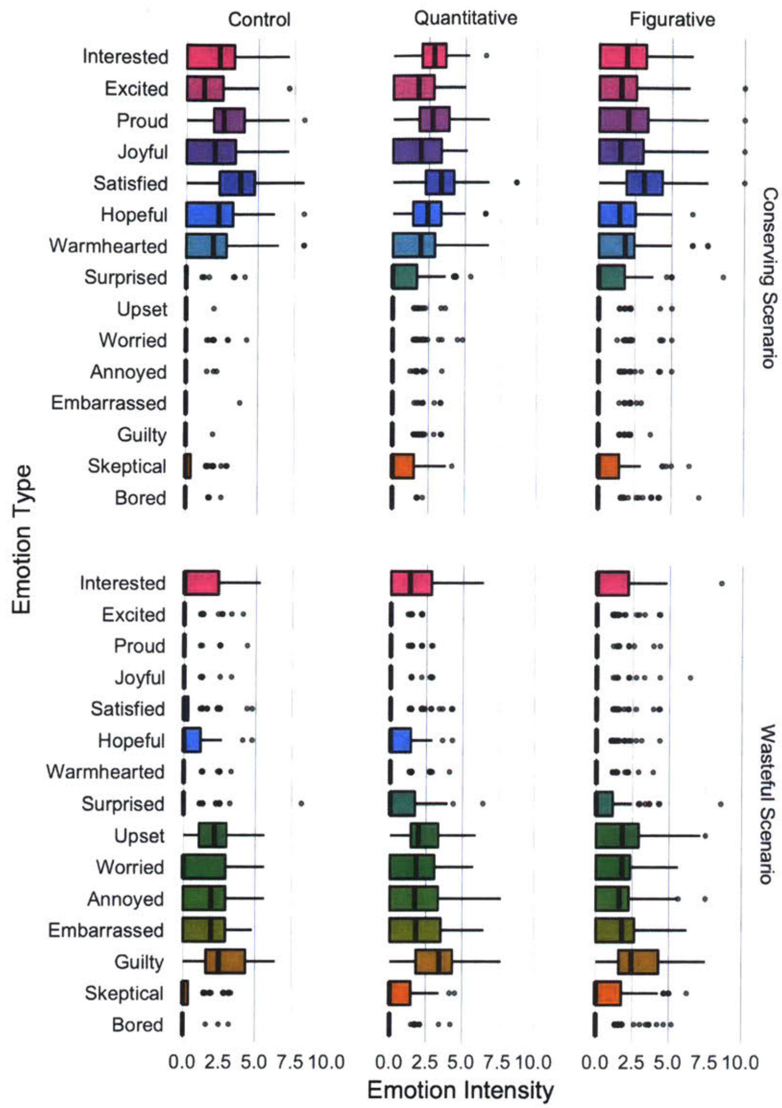


Figure 5-3: Distributions (boxplots) of intensity of 15 emotions in conserving (above) and wasteful (below) scenarios

It was expected that participants in the control group would not have strong emotional reactions in the product usage scenarios, since the neutral designs shown to them had little or no feedback information. However, contrary to our expectation, they did report strong emotions, mostly by reflecting on their experience of consuming electricity and water. In interviews, control group participants reported feeling *satisfied* and *joyful* in the conserving scenarios when they succeeded in saving resources, not necessarily because they contributed to the environmental sustainability, but could also because they saved money with a lower water or utility bill. They Would also be *proud* of themselves because they remembered and took effort to conserve resources. Similarly, these participants reported that they would be *upset* or *annoyed* with themselves or would feel *guilty* about wasting if they forgot to or could not conserve resources. *Warmhearted* and *hopeful* feelings would arise when they felt that a simple action or small effort of theirs could effectively reduce their electricity or water consumption. Although some of these participants expressed *excitement* and *interest* in the products as they thought the designs looked "stylish" or "modern", most of their emotions were not directly related to the designs, but were instead tied to their past experiences and their own attitude toward resource conservation.

In contrast, in quantitative and figurative groups, the reported emotions were not only strongly linked to resource consumption or conservation, but also linked to the designs. For example, participants reported in the interviews that they would feel *upset* because of the sad animal images in the figurative designs and would feel *guilty* if they associated their behaviors with harm to the environment and wildlife. Similarly, they would feel *joyful* when seeing happy animal images or a thank you note displayed on the design, or they would feel *satisfied* when the products told them they achieved the goal of resource conservation (and if they also agreed with the goal). They could be *annoyed* by products if they felt the designs were manipulative or reminded them of their resource usage over and over again. In addition, participants in the quantitative and figurative groups were *surprised* and *skeptical* noticeably more often than participants in the control group. They could be *surprised* by the information or graphics presented in the designs, such as the "150 L water per load" message on the washing machine button, which was the unexpectedly large volume of water used by a traditional washing machine; or the stylistically decapitated polar bear on the light switch. They could also be *skeptical* about how accurately these devices could track resource usage.

5.4.4 Designs and Emotions

To simplify the comparison of emotions between designs, principal component analysis was conducted with emotions in conserving scenarios and emotions in wasteful scenarios. The most significant principal components (PCs) in the two scenarios could explain 75% and 66% of their respective variances and thus were used as representations of the emotions in each scenario. The PC in conserving scenarios was highly correlated with positive emotions such as *satisfied*, *proud*, *interested*, and *joyful*; the PC in wasteful scenarios was highly correlated with negative emotions including *guilty*, *upset*, *embarrassed*, and *annoyed*. Table 5.4 summarizes the factor loadings of the first principal components in the two scenarios.

During interviews, notable differences in opinion were observed between younger and older participants, especially towards the figurative designs. Older participants generally

Table 5.4: First principle components of emotions in conserving and wasteful scenarios

		Conserving Scenario	Wasteful Scenario
Factor loading	Interested	0.356	0.225
	Excited	0.301	0.055
	Proud	0.414	0.028
	Joyful	0.354	0.025
	Satisfied	0.503	0.047
	Hopeful	0.318	0.079
	Warmhearted	0.321	0.037
	Surprised	0.136	0.131
	Upset	0.014	0.419
	Worried	0.045	0.345
	Annoyed	0.022	0.380
	Embarrassed	0.019	0.383
	Guilty	0.026	0.563
	Skeptical	0.078	0.116
	Bored	0.021	0.039
Percentage of variance		74.8%	66.3%

didn't associate the polar bear or the seal on an iceberg with global warming, and thus didn't link the animal figures to the consumption of energy. In contrast, younger participants generally recognized the symbolic meaning of arctic animals and considered them appropriate reminders to conserve energy. In addition, the cartoonish image style was criticized by older participants, but was well accepted among younger ones.

Therefore, we divided the participants into younger and older age groups, with 37 years old as the cut-off age. This cut-off age was chosen as it was the borderline of two generation cohorts: the Millennials, and Generation X and older. Additionally, it was close enough to the participants' median age (35 years old) that each age group had enough participants for meaningful statistical comparison (control, quantitative and figurative groups each had 7, 15, and 16 participants in the younger group, and 7, 11 and 12 participants in the older group). We not only compared emotions between the experimental groups, but also compared emotions between the younger and older age groups. Figure 5-4 shows the distribution of the emotion principal components towards the four products within each experimental group and each age group.

It can be observed that older participants in the figurative group generally reported less intense emotions in both conserving and wasteful scenarios. Analysis of variance (ANOVA) was conducted to detect if these differences were significant. Emotions towards all four products were pooled together for the analysis. BH method was applied to adjust the p-values. The results are summarized in Table 5.5.

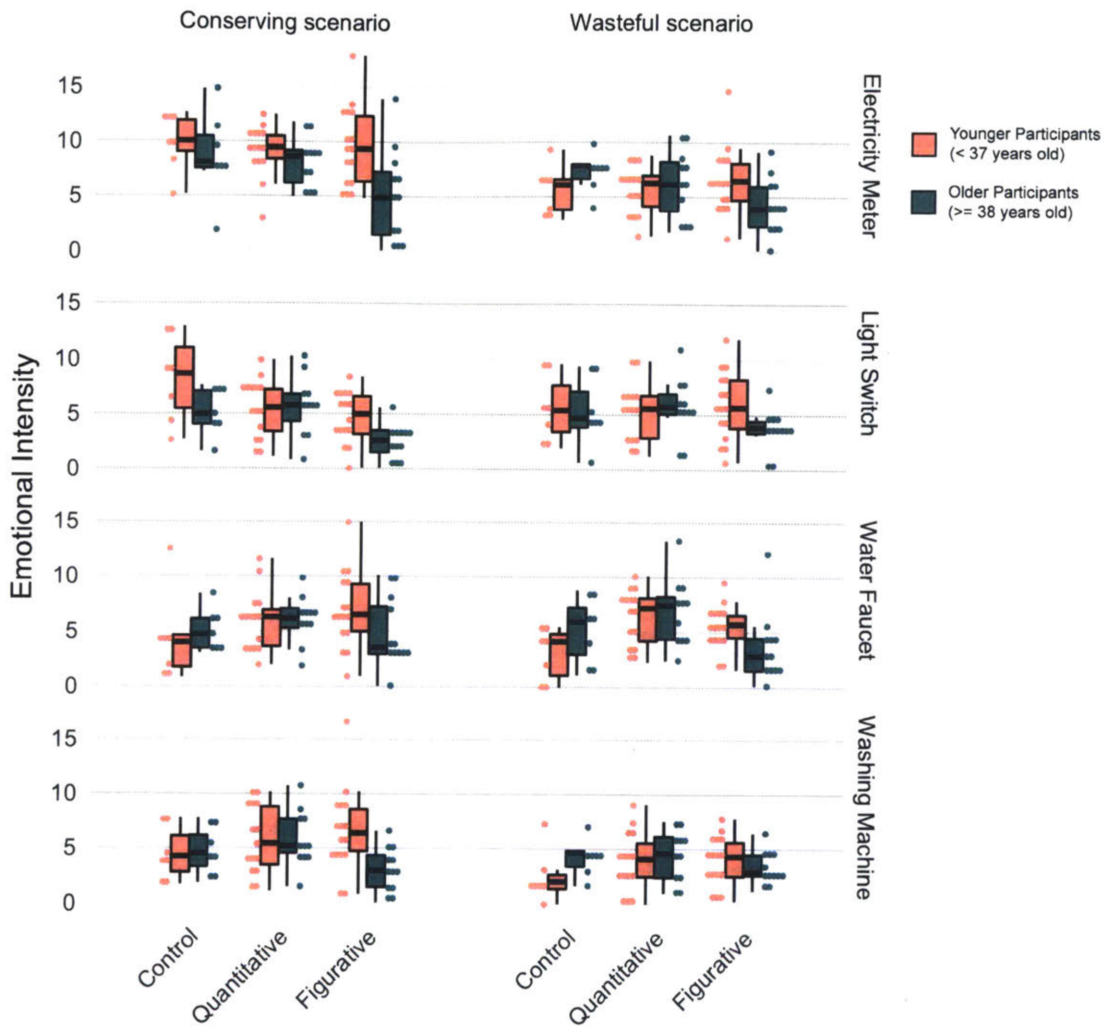


Figure 5-4: Comparing emotion principal components between experimnetal groups and between age groups

Note: This graph uses both boxplots and dotplots to illustrate the distributions of the emotion principal components. The boxplots show the overall distributions and make it easier to compare distributions between groups, while the dotplots provide more details with raw data.

In figurative group, the emotional intensity of older participants was on average significantly lower than that of the younger participants. The differences between age groups within the control group and within the quantitative group were not significant. In addition, significant differences were detected between older participants in different experimental groups. Further pairwise comparisons showed that older participants' emotional intensity was significantly lower in the figurative group, compared to either the control group or the quantitative group, in both conserving and wasteful scenario (conserving scenario: F-value = 8.276 and 19.441, adjusted p-value = 0.008 and <0.001; wasteful scenario: F-value

Table 5.5: ANOVA on emotion principal components between experimental groups and between age groups

		Conserving scenario	Wasteful scenario
Between younger & older participants	in control group	0.747 (0.652)	3.360 (0.102)
	in quantitative group	0.104 (0.817)	0.652 (0.421)
	in figurative group	23.165 (<0.001)	13.409 (0.001)
Between experimental groups	among younger participants	0.202 (0.817)	2.549 (0.102)
	among older participants	10.290 (<0.001)	8.405 (0.001)

Note: ANOVA results are presented as F-value (adjusted p-value). Results significant on 0.05 levels are highlighted in gray.

= 9.629 and 14.850, adjusted p-value = 0.004 and <0.001, compared to control group and quantitative group, respectively). No significant differences were detected between the three experimental groups among the younger participants.

To detect if any other demographic factors or the environmental attitude of participants had influence on users' emotional intensity, linear regressions were conducted between the emotion principal components and participants' age, gender, level of education, and pro-environmental attitude scores:

$$EmotionPC \sim Group_Q + Group_F + Attitude + Age + Gender + EL2 + EL3 \quad (5.3)$$

where $Group_Q$ and $Group_F$ were dummy variables for quantitative and figurative groups, respectively. Attitude score and age were normalized to be centered around 0 with standard deviation of 1. Gender was a dummy variable (female = 1, male = 0). $EL2$ and $EL3$ were dummy variables for the level of education ($EL2$ bachelor's degree or equivalent, $EL3$ master or PhD degree).

For the first principal component of emotions in conserving scenario, pro-environmental attitude score (β = 0.642, p = 0.002) and age (β = -0.681, p = 0.002) were significant predictors. $Group_Q$ (β = 0.072, p-value = 0.895), $Group_F$ (β = -0.858, p = 0.115), gender (β = -0.110, p = 0.796), and education levels ($EL2$ β = -0.086, p = 0.871, $EL3$ β = -0.504, p = 0.376) were not significant predictors. The intercept β was 6.703, p < 0.001. The overall model fit was R-squared = 0.080, F(7, 264) = 3.263, p-value = 0.002.

For the first principal component of emotions in wasteful scenario, only pro-environmental attitude score (β = 0.558, p = <0.001) was significant predictor. $Group_Q$ (β = 0.600, p-value = 0.175), $Group_F$ (β = -0.128, p = 0.771), age (β = -0.137, p = 0.425), gender (β = -0.159, p = 0.642), and education levels ($EL2$ β = -0.806, p = 0.061, $EL3$ β = -0.300, p = 0.514) were not significant predictors. The intercept β was 5.461, p-value < 0.001. The overall model fit was R-squared = 0.075, F(7, 264) = 3.037, p-value = 0.004.

Positive links were found between the participants' pro-environmental attitude scores and their emotion PCs in both conserving and wasteful scenario, indicating the emotions revealed in the study to a certain extent reflected participants' pro-environmental attitudes. Negative link was found between age and the emotion PC in conserving scenario, consistent with the previous ANOVA analysis.

5.4.5 Resource Conservation Action and Design Evaluation

Figure 5-5 summarizes participants' reported certainty of taking immediate resource conservation actions when using the four products.

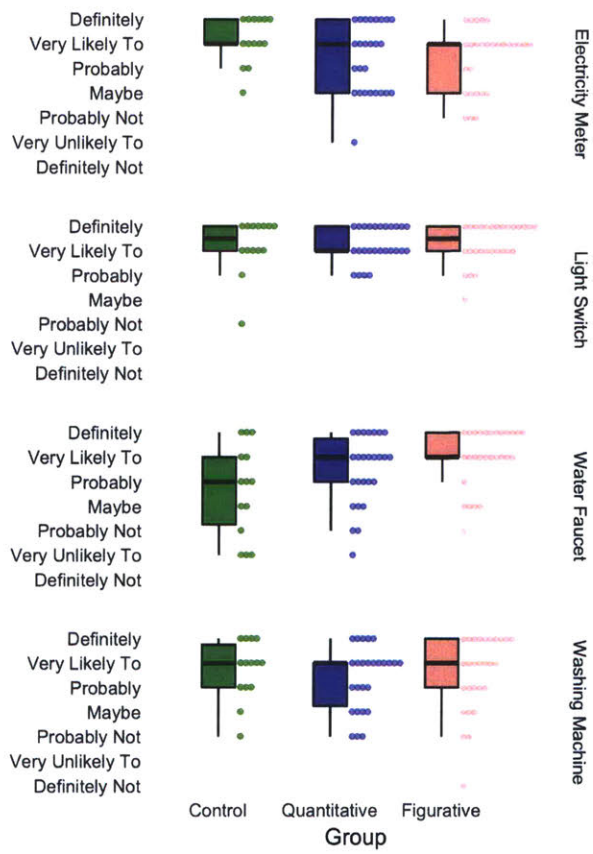


Figure 5-5: Certainty of taking immediate conservation actions

Note: Similar to Figure 5-4, this graph uses both boxplots and dotplots to illustrate the distributions of the certainty of taking immediate conservation actions. The boxplots show the overall distributions, while dotplots show the raw data.

In the control group where the products provided little or no feedback information, participants were much more likely to conserve energy than conserve water. From the interviews we learnt that some participants didn't pay water bills as they were included in the rents of their residences. However, they needed to pay electricity bills as they were not included in rent. This could partially explain why some participants were more cautious about electricity consumption than water consumption. Consequently, the majority of participants reported that they would definitely or were very likely to track their electricity usage to conserve electricity, or to turn off lights when leaving a room, as these were habits they had already developed. However, they were less likely to turn off a water faucet while washing dishes as it was inconvenient, and were more reluctant to use the low water usage mode in the washing machine as there was a risk of leaving detergent residue in their clothes.

In quantitative and figurative groups, participants might or might not behave differently after seeing the feedback information on resource consumption. ANOVA was conducted to detect if the differences between experimental groups were statistically significant, the results of which are summarized in Table 5.6. There existed significant differences between experimental groups regarding the certainty of turning off a water faucet. Providing feedback on water usage seemed to make the participants much more likely to conserve water. Participants commented that the feedback information on the faucet made them aware of their water usage, which would be otherwise neglected easily. Further pairwise comparisons showed that participants' certainty of turning off water faucets was significantly higher in the figurative group than in the control group (ANOVA F-value = 8.263, adjusted p-value = 0.019).

Table 5.6: ANOVA on conservation actions and design evaluations between experimental groups

	Action	Aesthetics	Usefulness	Willingness To Use	Overall Evaluation
Electricity Meter	1.551 (0.435)	0.577 (0.600)	3.263 (0.134)	6.105 (0.032)	2.155 (0.196)
Light Switch	0.148 (0.936)	10.464 (0.008)	0.666 (0.417)	8.284 (0.022)	7.887 (0.026)
Water Faucet	7.551 (0.031)	2.143 (0.296)	3.987 (0.134)	2.434 (0.165)	5.464 (0.045)
Washing Machine	0.000 (0.987)	0.055 (0.816)	2.777 (0.134)	0.000 (1.000)	1.261 (0.266)

Note: BH method was applied to adjust the p-values. ANOVA results are presented as F-value (adjusted p-value). Results significant on 0.05 levels are highlighted in gray.

Results of the four design evaluations (*aesthetics, usefulness, willingness to use* and *overall quality*) are summaried in Figure 5-6. They were highly correlated with each other (Pearson correlation coefficients ranging from 0.48 to 0.74). Again, ANOVA was conducted to compare the overall design evaluations between groups, the results of which summarized in Table 5.6. Further pairwise comparisons were conducted between experimental groups when significant differences were detected.

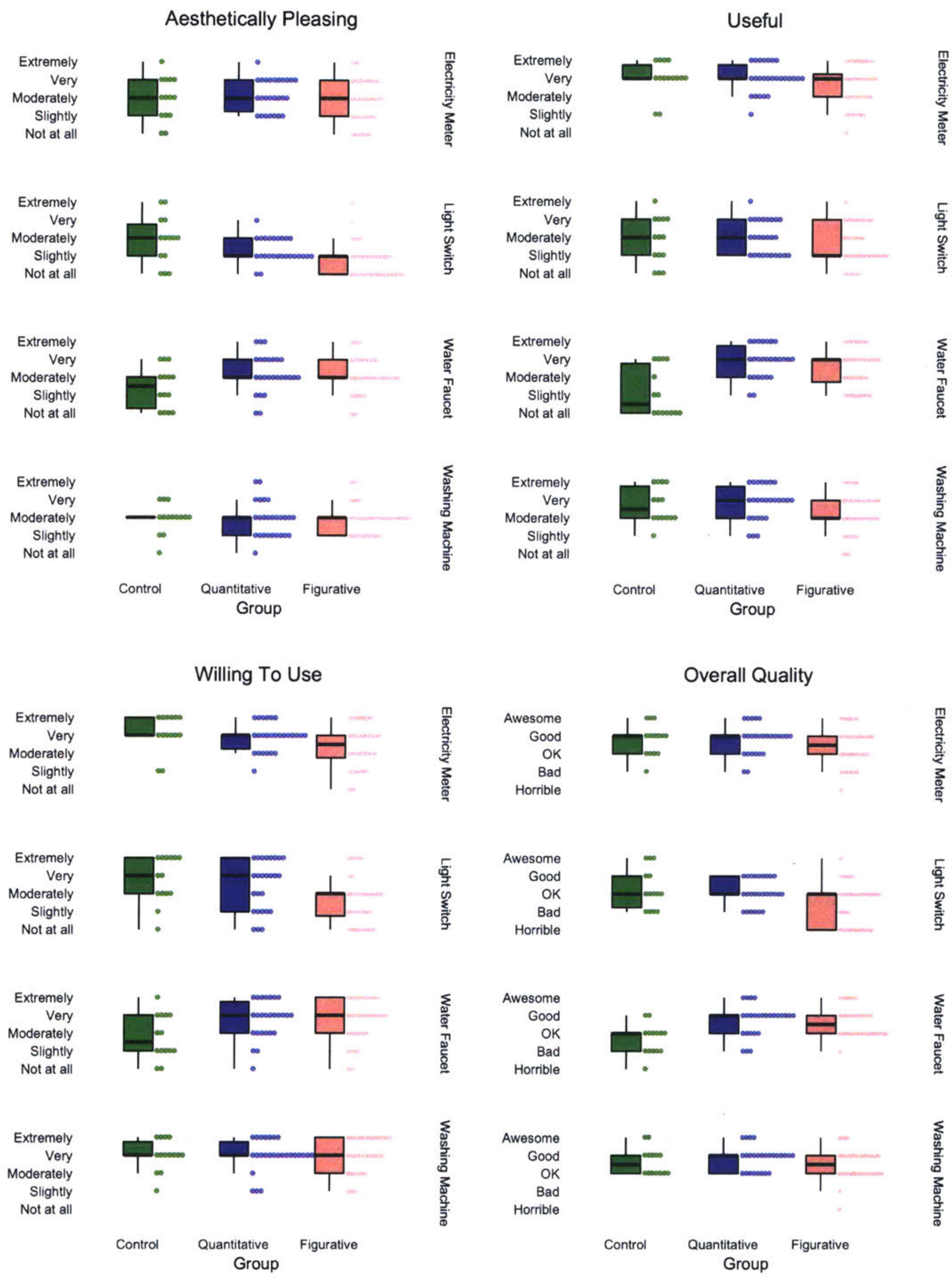


Figure 5-6: Design evaluations

With regard to electricity meters, participants in the quantitative and figurative groups overall reported they were less likely to take the suggestions to conserve electricity compared to the control group participants. When seeing the detailed information on the electricity meter display, participants questioned how the target usage was selected and how the electricity conservation suggestions were provided. They commented that they would take more factors into consideration. For example, if it was an extremely hot summer day, they would not turn off the air conditioner even if the electricity meter suggested doing so. In addition, the figurative group participants in general commented that they were more interested in the quantitative data of electricity consumption and would like to know more about when and where the electricity was consumed. They were less interested in the seal on iceberg animation since it didn't provide much useful information. Pairwise comparisons showed that the willingness to use rating for the figurative electricity meter was marginally lower than that of the neutral and the quantitative electricity meter designs (F-value = 3.861 and 3.487, adjusted p-value = 0.056 and 0.068).

Compared to the neutral design and the quantitative design of the light switch, the figurative design with polar bear image had significantly lower aesthetics rating (F-value = 7.728 and 4.827, adjusted p-value = 0.025 and 0.049); significantly and marginally lower willingness to use rating (F-value = 6.889 and 4.751, adjusted p-value = 0.037 and 0.051); and marginally lower overall quality rating (F-value = 4.513 and 5.543, adjusted p-value = 0.060 and 0.060). For the neutral design, participants in general thought the design was modern looking, and the light switch button was large and thus would be easy to use. As for the quantitative design, participants in general thought the information about energy consumption was useful, though some of them commented that they didn't know how much 120 Watts of electricity was. Also, it was pointed out that the text was small and thus might not attract attention, and that it made the design less aesthetically pleasing. Comments on the figurative light switch design were polarized. Many participants thought the graphic of a decapitated polar bear was too violent and thus considered it inappropriate, while the others agreed that the graphic was extreme however thought it was funny. A few participants thought the design clearly conveyed the idea that conserving electricity would contribute to environmental sustainability and therefore would be effective in encouraging people to turn off lights, while another few participants commented that the design was manipulative and thus would drive people away.

As for the water faucet, the quantitative and figurative designs both had higher overall quality ratings than the neutral design (F-value = 14.447 and 13.506, adjusted p-value = 0.001 and 0.001, respectively). When looking at the neutral design, the participants mostly focused on product usability: how to turn it on/off and adjust water volume and temperature. Most participants considered the design unintuitive and gave it low ratings on design evaluations. In contrast, when looking at the quantitative and figurative designs, participants' attention was focused on the display of water usage and they tended to give those designs higher ratings. The fish image on the figurative water faucet design was much better accepted by the participants than the polar bear image on the light switch design, seemingly because the metaphorical link between fish and water was considered more direct and obvious than the link between polar bear and electricity. Also, even though the GIF animation indicated that using too much water would eventually drain the water tank of the fish, it didn't directly show any image of the fish being harmed, and thus was considered milder.

5.4.6 Links between User Emotions, Behaviors, and Design Evaluations

To identify links between user emotions regarding using eco-feedback products and users' resource conservation behaviors, Pearson correlations were calculated between the emotion principal components and the certainty of taking immediate resource conservation actions. In addition, correlations were calculated between the emotion principal components and the four design evaluations. The correlation analysis results are summarized in Table 5.7.

Table 5.7: Correlation between certainty of conservation actions, design evaluations, and emotion principal components

		Control Group	Quantitative Group	Figurative Group
Emotion PC in Conserving Scenarios ×	Action	0.365 (0.028)	0.142 (0.149)	0.060 (0.531)
	Aesthetics	0.085 (0.658)	0.327 (0.002)	0.353 (<0.001)
	Usefulness	0.154 (0.641)	0.290 (0.005)	0.367 (<0.001)
	Willingness To Use	-0.066 (0.658)	0.202 (0.049)	0.121 (0.257)
	Overall Quality	0.06 (0.658)	0.337 (0.002)	0.303 (0.002)
Emotion PC in Wasteful Scenarios ×	Action	0.535 (<0.001)	0.442 (<0.001)	0.234 (0.033)
	Aesthetics	0.119 (0.708)	0.097 (0.408)	0.207 (0.047)
	Usefulness	-0.011 (0.935)	0.185 (0.150)	0.256 (0.033)
	Willingness To Use	0.109 (0.708)	0.134 (0.292)	0.061 (0.520)
	Overall Quality	0.050 (0.891)	0.080 (0.421)	0.163 (0.108)

Note: BH method was applied to adjust the p-values to reduce false detections of significant correlations. Pearson correlation results are presented as *correlation coefficient (adjusted p-value)*. Correlations significant on 0.05 levels are highlighted in grey.

In the control group, the certainty of participants taking immediate actions to reduce electricity/water waste was significantly positively correlated with both the emotion principal component in conserving scenarios (representing positive emotions such as *satisfied, proud, interested*, and *joyful*) and the emotion principal component in wasteful scenarios (representing emotions such as *guilty, upset, embarrassed*, and *annoyed*). This was consistent with the interview results that in situations where the participants had strong intensity to take actions to conserve resources, they would express positive emotions towards saving and express negative emotions towards wasting; and in situations where they didn't feel the necessity of conserving resources, they wouldn't feel as strongly about wasting or conserving. Actually, it was observed that the feeling of *satisfied* in the wasteful scenario was significantly negatively correlated with the certainty of conservation action in the control group (correlation coefficient = -0.53, adjusted p-value < 0.001), indicating positive emotions towards consumption instead of conserving. In addition, no significant correlations were found between the emotion principal components and the design evaluations in the control group, confirming the observation that the emotions in the control group were not directly evoked by the designs (see section 5.4.3).

In the quantitative and figurative groups, the positive correlations between certainties of conservation actions and the emotion PCs were still statistically significant in wasteful scenarios, however no longer significant in conserving scenarios. There were presumably multiple reasons behind this phenomenon. First, as described earlier, figurative designs significantly reduced emotions in some participants, however, did not significantly reduce the certainty of taking actions and in some scenarios even increased the certainty (see section 5.4.4). This could potentially explain the decreasing of correlations between emotions and certainty of conservation actions. Secondly, in actionable scenarios (where participants answering questions of how likely they were going to take actions to conserve resources), the participants were presented with product sketches (or GIF animations) corresponding to those in wasteful scenarios. This might explain why certainty of taking actions was more correlated with the negative emotions in wasteful scenarios than with the positive emotions in conserving scenarios.

More interestingly, significant correlations were found between emotion PCs and design evaluations in the quantitative and figurative groups, demonstrating strong links between user emotions and their perceptions of the designs. In general, design evaluations were significantly correlated with positive emotions in conserving scenarios in both quantitative and figurative groups, suggesting the importance of fostering positive emotions in eco-feedback designs: if a product made the users feel good about conserving resources, they would be more engaged with the product in the long run. In the figurative group, the negative emotions in wasteful scenarios were also significantly correlated with the evaluation on products' aesthetics and usefulness on encouraging sustainable behavior. One potential explanation was that, participants who appreciated the drawing style of the figurative designs (that is, gave them higher aesthetics ratings) would more likely to empathize with the animals presented on the designs (with stronger feelings of *guilty, upset*, etc. when seeing images of sad animals), and also thought these emotions were effective in encouraging resource conservation behavior (gave higher usefulness ratings). However, it should be noted that correlations between positive emotions and design evaluations were much stronger, even in the figurative group. As revealed by the post-study interviews, if a product made the users feel bad, the users might avoid interacting with the product in order to keep away negative feelings.

Linear regressions were further conducted between the certainty of resource conservation action, design evaluations, and participants' demographic factors and pro-environmental scores. Emotion principal components were included in the regression models as independent variables:

$$\begin{aligned} Y \sim & \, Group_Q + Group_F + Attitude + Age + Gender + EL2 + EL3 \\ & + EmotionPC_C + EmotionPC_W \end{aligned} \tag{5.4}$$

where Y could be the certainty of resource conservation action or any of the four design evaluations, and $EmotionPC_C$ and $EmotionPC_W$ were normalized emotion principal components in conserving and wasteful scenarios, respectively. The other independent variables were defined in the same ways as in equation 5.3. Linear regression results are summarized in Table 5.8.

Consistent with the previous correlation analysis, certainty of conservation actions was significantly linked to the emotion principal component in wasteful scenarios, and almost all design evaluations were significantly linked to emotion principal component in conserving scenarios. Interestingly, pro-environmental attitude was not significantly linked with the certainty of resource conservation actions or any design evaluations, even though earlier we have seen that attitude was significantly linked with both the emotion principle components in conserving and wasteful scenarios (see section 5.4.4). This indicates that compared to pro-environmental attitude, user emotions were better predictors of their resource conservation behavior and their perceptions of the eco-feedback designs.

Age was negatively linked with the aesthetics rating, consistent with the observation that older participants appreciated the cartoon styled drawings less. In addition, level of education was significantly linked with all four design evaluations: the higher a participant's education level was, the lower they tended to rate the designs.

5.5 Discussion

Key findings of the study are highlighted below and discussed in response to the original research questions:

Q1: What are the emotions that arise from users' interactions with eco-feedback products?

For this study we used a discrete emotion perspective [206, 207], treating emotions as

Table 5.8: Linear regression for certainty of resource conservation actions and design evaluations on user emotions and demographics

		Action	Aesthetics	Usefulness	Willingness To Use	Overall Quality
β (p-value)	(Intercept)	5.665 (<0.001)	3.039 (<0.001)	3.716 (<0.001)	3.996 (<0.001)	3.604 (<0.001)
	$Group_Q$	-0.199 (0.330)	0.111 (0.517)	0.492 (0.006)	0.070 (0.725)	0.277 (0.079)
	$Group_F$	0.117 (0.564)	-0.021 (0.900)	0.176 (0.323)	-0.263 (0.182)	-0.019 (0.901)
	Attitude	0.112 (0.154)	-0.123 (0.062)	-0.040 (0.561)	0.059 (0.436)	-0.085 (0.164)
	Age	0.000 (0.997)	-0.150 (0.027)	-0.008 (0.914)	-0.045 (0.564)	-0.122 (0.051)
	Gender	0.117 (0.458)	-0.100 (0.447)	-0.165 (0.233)	-0.11 (0.473)	-0.100 (0.411)
	EL2	0.102 (0.610)	-0.206 (0.217)	-0.535 (0.002)	-0.144 (0.455)	-0.245 (0.112)
	EL3	-0.075 (0.724)	-0.380 (0.033)	-0.737 (<0.001)	-0.522 (0.012)	-0.362 (0.028)
	$EmotionPC_C$	-0.033 (0.702)	0.270 (<0.001)	0.313 (<0.001)	0.064 (0.440)	0.239 (<0.001)
	$EmotionPC_W$	0.504 (<0.001)	0.070 (0.326)	0.052 (0.484)	0.082 (0.321)	0.019 (0.767)
	R-squared	0.159	0.143	0.183	0.065	0.137
	F(9, 262)	5.504	4.861	6.508	2.011	4.624
	p-value	<0.001	<0.001	<0.001	0.038	<0.001

Note: Linear regression coefficients significant on 0.05 levels are highlighted in gray.

distinguishable units and providing study participants with emotion labels to rate. We chose commonly used labels such as *proud* and *guilty*, assuming these could be recognized and consciously reported. Our analysis also relied upon a dimensional model of emotions [208] and used positive affect and negative affect measurements of participants to normalize the intensity of their emotional responses.

By providing study participants with product usage scenarios, we successfully revealed not only visceral emotions towards the appearance of the designs, but also behavioral emotions towards using the products and reflective emotions towards the consumption and conservation of resources [59]. In the control group where participants seeing designs with little or no feedback information, their reported emotions mostly came from past experience of consuming or conserving electricity and water, and reflected their attitudes towards resource conservation. In a scenario where a user successfully conserved resources, positive emotions such as *satisfied* and *proud* tended to dominate. In a scenario where a user failed to conserve resources, feelings such as *guilty, embarrassed* or *upset* were likely to arise.

In quantitative and figurative groups where the designs were embedded with feedback information on resource consumption and explicitly encouraged conservation behaviors, the revealed user emotions were a mix of these behavioral and reflective emotions, and emotions directly elicited by the designs. Eco-feedback information could enhance positive emotions towards saving and negative emotions towards wasting, and users may empathize with the animals in the figurative designs by experiencing negative emotions when seeing sad or dying animal images and experiencing positive emotions when "saving" the animals and seeing happy animal images. These emotions seem likely to have been generated by a combination of both bottom-up and top-down processes [209]: emotions could either be triggered directly by visual stimuli in the sketches (such as a decapitated polar bear) or arise via higher-level cognitive interpretations drawing upon stored knowledge (such as the fact that greenhouse gas emissions accelerate global warming and thus endanger wildlife). In this experimental setting it was difficult to tease out how much each process might have been involved in the generation of a particular response.

Eco-feedback products generally made people *curious* about their resource consumption, even though some users were *skeptical* about the accuracy of the feedback information. Additionally, the quantitative designs and figurative designs were more likely to *surprise* participants compared to the neutral designs. On one hand, this validated the use of neutral designs in the control experimental setting; on the other hand, this indicated that the eco-feedback designs would be eye-catching and would attract users' attention. This is actually important, as when users are interacting with products in their daily lives, they may not think about resource consumption all the times and thus waste resources unintentionally. Whether a design can successfully attract users' attention in the first place is the premise of whether it can effectively encourage sustainable behavior. If a design can introduce cognitive dissonance in users by catching them in surprise, there is a chance that the users might change their behavior to resolve the dissonance [210].

Q2: What role do emotions play in influencing users' sustainable behavior and their perceptions of eco-feedback products?

Human behavior is a product of complex interactions between the cognitive and the affective systems of our brains [211]. There are multiple mechanisms by which emotion can shape behavior: sometimes rapid, automatic affective responses directly influence immediate decision making and behavioral choice, while at other times emotions influence behavior less directly, by providing feedback, promoting learning, or altering guidelines for future behavior [212].

In this study, the reported certainty of taking immediate conservation action was used as a measure of product usage behavior. Since tradeoffs for convenience were included in the actionable scenarios, we collected responses spanning from "definitely" to "definitely not" taking conservation actions. In all experimental groups, significant correlations were found between certainty of taking conservation action and negative emotions in wasteful scenarios. This suggests that negative emotions could be effective in encouraging sustainable behaviors, if used properly. Negative emotions should not be entirely avoided in product design as they could potentially enrich the user experience [213]. But we acknowledge there is a subtle line between a user expecting themselves to feel negatively about wasting resources, and a design that intentionally making users feel negative emotions. If the negative emotions evoked by a design are not aligned with users' intentions of conserving resources, they may avoid further interaction with the design. The figurative design of the light switch in our study provided an example. It showed a polar bear that was stylistically decapitated by turning the light switch on. The majority of participants who saw this design reported that they would "definitely" turn off the light to avoid the guilty feeling of "killing" the polar bear. However, many of them did not like the design and would not want to use it because they would "not be able to turn on the lights at all"; or they would just ignore the design and desensitize themselves from the negative feelings. This is consistent with the point of view from existing literature that designers should avoid making users feel guilty [173].

On the contrary, the evaluations of designs' Aesthetics, Usefulness, and Overall Quality in both the quantitative and figurative groups were significantly correlated with positive emotions in conserving scenarios. This suggests that positive reinforcement and using positive emotions to reward users would be a favorable strategy to attract users and (as long as liking a product is correlated with actually using it, a sensible proposition beyond the boundary of this study) keep them engaged in sustainable behaviors in the long run.

Q3: How can we design eco-feedback products to evoke strong and appropriate emotions in users to encourage sustainable behavior?

Two styles of eco-feedback designs were compared in this study: quantitative designs that emphasize objective resource usage information, and figurative designs that use animal figures as reminders of environmental sustainability. In addition, we created a group of neutral designs which provided little or no feedback information. In the study conducted with university students documented in the last chapter, designs with animal figures were evaluated as more "emotionally evocative" than quantitative designs. However, in this study, the intensity of emotional reactions towards the two design styles was not significantly different among participants in the younger age group, which represented the Millennial cohort. This is likely because the emotions evaluated in the previous study were more on the visceral level which was concerned with the appearance of the designs, while the user emotions revealed in this work were more on the behavioral level and reflective level that were concerned with using the products and conserving resources.

Additionally, we observed that figurative designs evoked much stronger emotions in younger participants than in the older participants: the figurative designs actually seem to suppress emotions in the older participants. This discrepancy could be explained by the differences between two generations: while the use of arctic animals as symbols of global warming and environmental sustainability was well-known among the younger generation, it was not common knowledge among the older generation; and the cartoonish drawing styles were better accepted by the younger than by the older. This finding provided important lessons for designing emotionally evocative eco-feedback designs for different audiences: a cartoonish design could well fit into a school environment to educate children about resource conservation; it could also fit into a college dorm to initiate discussion about environmental sustainability among students; but it might be less appropriate for a formal workplace where more serious designs are expected.

Among the four products tested, the eco-feedback water faucet appeared to significantly increase the reported certainty of users conserving water and had significantly higher ratings on overall quality compared to the faucet without feedback information. A few features of the eco-feedback water faucet that users liked were pointed out in the post-study interviews. First, eco-feedback information was embedded in the faucet in a noticeable way that users would be unlikely to miss when using it (while the users could choose to not interact or forget to interact with the electricity meter and the light switch). Secondly, the eco-feedback information was presented in a concise and neutral manner in the water faucet. Compared to the electricity meter design, the water faucet did not set any target usage, which provided users with flexibility in terms of how much resources to use. It also avoided the potential mental accounting effect of goal setting: if the usage was lower than the target, users might feel they could use more and thus result in more wasting than saving. And lastly, the fish image in the figurative design was in general considered good metaphorical symbol of water conservation. While the message of saving water was clearly conveyed, the graphic itself was not as violent or depressing as some other figurative designs might be. These observations pointed to the importance of keeping a balance between eye-catching and unobtrusive, being instructive but not manipulative, and providing trustworthy information in eco-feedback designs.

5.6 Conclusion

This study has improved our understanding of emotions that arise from users' interactions with eco-feedback products. It was found that higher certainties of users taking immediate actions to conserve resources were linked to stronger negative emotions towards wasting such as *guilty, embarrassed*, and *upset*; however, users' perception of the designs' aesthetics, usefulness and the overall quality were more correlated with positive emotions towards resource conservation, such as *satisfied, proud, interested*, and *joyful.* This suggests that evoking negative emotions in users may be an effective strategy for spurring immediate sustainable behaviors, while fostering positive emotions may be more important for engaging users with eco-feedback products in the long term. Longitudinal studies that observe users' interaction with eco-feedback products for longer periods of time could help to confirm these hypotheses and to reveal how user emotions may evolve over time.

Two styles of eco-feedback designs, quantitative and figurative, were tested and compared to neutral designs with little or no feedback information. It was found that participants in older age groups (who belonged to the Generation X and Baby Boomer cohorts) had very different emotional reactions towards figurative designs, which used animal figures as reminders of environmental sustainability, compared to younger participants and compared to their reactions towards the other designs. This result is helpful for forming guidelines to design more inclusive eco-feedback products, or design eco-feedback products for different generational cohorts.

In this study, preliminary design ideas presented in forms of sketches and GIF animations were used to evaluate users' emotional reactions towards the designs. In addition, detailed usage scenarios were created to help the participants report realistic emotions and behaviors. While further studies with physical products or prototypes should be explored to understand user emotions, we believe the method established here is useful to designers and design researchers in the early stage design as it enables the evaluation of many different ideas in a short amount of time.

Chapter 6

Contributions and Future Work

This dissertation addressed user-centered approaches to sustainable design. The focus of the work has been on the relationships between sustainable products and their users. The first chapter outlined related work in the areas of user-centered design and design for sustainability. In the following chapters, two classes of sustainable products, residential solar PV systems and eco-feedback products, were investigated as case studies. Chapter 2 and Chapter 3 documented interviews with solar stakeholders and surveys with homeowners to assess user preferences for solar PV systems and installation. Chapter 4 and Chapter 5 presented online surveys and in-lab experiments to understand users' emotional responses towards eco-feedback products, their perceptions of the products, and their product-use behavior.

In terms of the original question asked in Chapter 1: *How can we design lovable sustainable products, which are desirable and have strong emotional connections with users, to increase product adoption and to encourage sustainable product use?* Instead of giving a single answer, this dissertation provided a new perspective to investigate the question, that is to integrate two design frameworks: the user-centered design and design of sustainable products (Figure 6-1).

The contribution of this dissertation is twofold. First, it demonstrated the application of user-centered design techniques in understanding user needs and gathering user feedback for sustainable products. This supplements the literature in investigating the "people" or "social" aspects [17] of sustainable product design. Second, knowledge was gained about sustainable product design, especially about the design of residential solar PV systems and eco-feedback products.

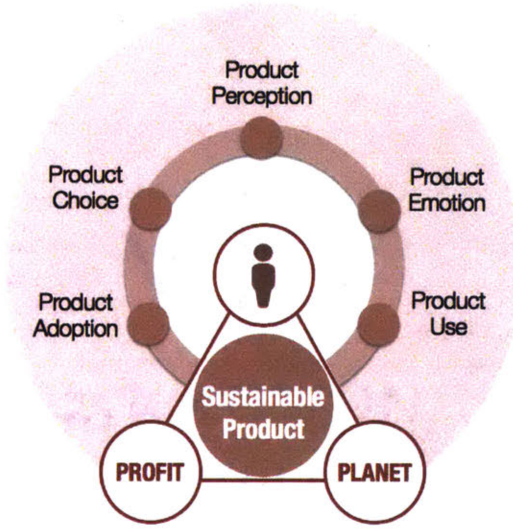


Figure 6-1: An integrated perspective of applying user-centered design to design of sustainable products

6.1 User-Centered Approaches in Design for Sustainability

A variety of user-centered design methods have been applied in this dissertation to investigate the relationships between sustainable products and their users, including stakeholder interviews to identify user needs for renewable energy systems, discrete choice experiments to assess user preferences for renewable energy products and services, collecting user feedback towards provisional eco-feedback product ideas, and investigating user emotional responses towards products designed to encourage sustainable use.

These methods were tailored for each application and their novelty lies in their execution and their quantitativeness. The author hopes the methods documented in this dissertation are informative to designers and design researchers and will help them prepare their own studies.

- Applied discrete choice experiments to study renewable energy systems and installation from product and service design perspectives

Chapter 2 and 3 documented details of the identification and selection process of key attributes of solar PV systems and installation. These attributes were on a design-level, which homeowners are familiar with and refer to in their decision making on adopting solar. In the discrete choice experiments, these attributes were introduced to survey participants in language that homeowners with little experience with solar PV systems would understand, which helped to reveal realistic preferences.

- Formulated a framework for investigating user emotional responses towards sustainable products

The experimental setup described in Chapter 5 established a framework for designers to investigate user emotions towards sustainable products and sustainable product use. The product-use scenarios successfully revealed user emotions on all three levels: the visceral, behavioral, and reflective.

6.2 User Needs and Preferences for Residential Solar PV and Installation

Traditional research in residential solar PV focused on improving the engineering performance of the PV systems [104–108]. This dissertation takes a user-centered design perspective and investigated user needs and preferences for the design of residential solar PV systems and the services provided by solar installers. The main contributions of this work are:

- Identified several key attributes of solar PV systems and installation that directly influence homeowners' decision making on adopting residential solar and assessed how homeowners made tradeoffs between these attributes

Via interviews with 18 stakeholders and surveys with 1773 homeowners in California and Massachusetts, savings on electricity bills, system reliability, installer warranty, and reviewers' rating for the installer were identified as the most important factors that homeowners would consider when making decisions on adopting residential solar PV systems. These results provide first-hand information on homeowners' needs and preferences for residential solar PV, which can inform solar manufacturers and installers in terms of their decision making on product and service design. These results can also be used to calibrate simulation models for predicting future solar adoption and analyzing the impact of policies on the solar market.

- Compared homeowners across demographics on their preferences for solar system and installation

Preference differences were detected between adopters and non-adopters, and based on homeowners' state, age, and income. For example, compared to those with lower income, homeowners with higher income had stronger preferences for the "delight features" of solar, such as cutting-edge equipment technology or more aesthetically pleasing solar panels. As another example, compared to younger homeowners, older homeowners had stronger preferences for longer warranties over shorter warranties. These findings suggest that PV manufacturers and installers should diversify their products and services to satisfy the needs of more users.

6.3 Emotional Design in Eco-Feedback Products

The way of presenting resource usage information in eco-feedback products is key to their effectiveness in encouraging sustainable behaviors in users. Traditionally, research focused on the quantitative clarity of eco-feedback information [35, 83]. This dissertation takes an emotional design approach and investigates the emotional aspects of eco-feedback products. The main contributions include:

- Demonstrated the importance of not only presenting quantitatively clear feedback information but also engaging users emotionally

Via a survey with 658 university students in the US and Saudi Arabia, it was found that eco-feedback designs that were rated to be both quantitatively clear and emotionally evocative were more likely to be chosen as students' favorite design. In addition, it was found that quantitative resource usage information in eco-feedback products was more helpful to respondents who could better estimate resource consumption, while emotional evocativeness of a design appealed to users with lower and higher resource consumption knowledge to a similar degree. These findings confirm the importance of designing emotionally evocative eco-feedback products.

- Explored the role of different emotions in influencing user behaviors and perceptions of the designs

Higher certainties of users taking actions to conserve resources were found to link with stronger negative emotions (e.g. guilt) towards wasting. Users' perception of the designs' aesthetics, usefulness, and overall quality were found to link with positive emotions (e.g. satisfied) towards resource conservation. These results suggest that evoking negative emotions in users may be an effective strategy for spurring resource conservation behaviors, while fostering positive emotions may be more important for engaging users with eco-feedback products in the long term.

- Gained understandings of how to design emotionally evocative eco-feedback products to better engage the users and to encourage sustainable product-use behaviors

Different visual techniques were tested in the studies. Images of living creatures and strong visual cues evoked strong emotions in university students. Older users, in general, did not respond to animal images in eco-feedback designs as strongly as younger users, likely because older users appreciated less of the cartoonish drawing style and less often associated animal images with environmental sustainability. These findings point to the importance of understanding the needs of different users and design more inclusive eco-feedback products.

6.4 Future Work

Integrating user-centered design with design for sustainability can help designers to better align the interests of human beings and the environment. In the future, it would be interesting to apply user-centered techniques to the design of other sustainable products and systems, such as alternative fuel vehicles and desalination plants. In addition, it would be interesting to integrate the findings of this dissertation into an empirical design framework to encourage designers to consider the user perceptions and emotions towards sustainable products. The framework could also be used to facilitate idea generation in the early-stage design and to help create new product concepts to protect environmental sustainability as well as foster human well-being.

There are several opportunities for future investigation of user preferences for residential solar PV systems. This current study was built on the assumption that different attributes of solar systems and installation are independent of each other. Future work should incorporate engineering models to provide more realistic bundles of attributes. It would also be interesting to combine stated preference models from surveys with revealed preference models from market data to gain insights into homeowners' decision making.

Extensions to the eco-feedback design studies could focus on testing the product ideas with physical prototypes to further validate the observations in the experiments. Another interesting direction for future research is to monitor longer-term user-product interactions and to observe how user emotions and product-use behaviors evolve over time. In addition, while this current study investigated individual users' perceptions of eco-feedback designs in product usage scenarios which were mostly private settings, community perception of eco-feedback designs in shared spaces and group emotions towards using such designs are intriguing topics worthy of further exploration.

Appendix A

Residential Solar PV Stakeholder Interview Outlines

A.1 Solar Owners Interview Outline

Please walk us through the process of you installing solar PV system.

Decision-Making

- Why did you decide to install solar PV system?
- Did you know anyone in person that installed solar PV systems before you did?
- Did you expect installing solar systems to save money on the long run?

Pre-Installation

- How did you research different systems and installers?
- How did you choose your installer?
- How did you pick the brand and style of the solar panels?
- What were the most important factors that influenced your choices?

Installation

- How long did the installation process take?
- Who took care of the permit to install the panels on the roof?
- How was the system interconnected with the utility grid?

After Installation

- Did it cost as much as you expected?
- Did it save on electricity bill as much as you expected?
- What kind of maintenance have you done to the system?
- Have your electricity use patterns changed after installation?
- Is there anything about your system that you didn't realize until it was installed?

A.2 Professionals Interview Outline

Please walk us through the process of you helping homeowners installing solar PV system.

Products

- How do solar installers choose suppliers for equipment (including panels, inverters, mounting system, etc.)?
- What are the most important factors that homeowners look into about solar PV systems and installation?

Financing

- What are the costs of installing solar PV system?
- How do installers set price?
- How do installers manage the financing for leasing?

Policy

- How do installers cooperate with utilities?
- How do installers deal with uncertainty with policies (ITC, net-metering, etc.)?

What do you think are the most important incentives/barriers for homeowners installing solar?

Appendix B

Solar Discrete Choice Experiment Attribute Introduction

(Note: the following introductions are the original ones as presented in the survey)

Next, you will imagine shopping for solar panels. If you have installed solar already, please bear with us and pretend this is your first time shopping for solar.

Imagine that you have just bought and renovated a house. You have budgeted extra money for upgrades. Friends have told you that solar panels are a good investment because you will save money on electricity in the long run. Your roof is new and has the correct orientation for solar panels. All other conditions are also perfect for solar. You are now seriously considering installing solar panels, and are exploring available options.

You learn that solar panels are usually sold by solar installers. You need to first choose the installer to work with, and then select the solar system to install. In the next section, you will first read seven pages of information that will help you to make educated decisions when choosing an installer. Please spend enough time on each page and read them carefully (the survey will not allow you to proceed if you spend too little time reading). After that, you will be given some questions to answer.

Solar Installers

A solar installer is a company that supplies and installs solar panels for homeowners. The major responsibilities of a solar installer include:

- Designing the solar system layout
- Selecting and installing the equipment
- Applying for construction and electricity permits
- Applying for rebates
- Maintaining the system

You discover a website for comparing the solar installers in your area. Below is an example profile of a solar installer on the website. Go to the next page to learn the details of each feature.

	Example Installer
Consumer Reports Rating	Good ★★★★☆
Installer-Customer Interaction	Collaborative
Equipment Technology	Standard technology
Total Project Time	2-month project time
Warranty	15-year warranty
Savings in 25 Years	40% savings

Independent Reviewer Rating

Imagine that an independent product testing organization (like Consumer Reports) has evaluated solar installers based on customer reviews and other factors, such as financial stability, years in the market and so forth. The website shows you installers with at least a three-star rating. The rating of an installer can be:

- Average (★★★☆☆)
- Good (★★★★☆)
- Excellent (★★★★★)

Installer-Customer Collaboration

Depending on the working style of the installer, their level of interaction with customers can be:

- Independent (requires limited input from customer)
- Moderately collaborative (requires some input from customer)
- Collaborative (works closely with customer)

Equipment Technology

Different installers provide equipment with different brands and modules. The equipment can be categorized by the technology they use:

- Cutting-edge technology (on the market for half a year or less)
- Standard technology (on the market for at least 2 years)
- Traditional technology (on the market for at least 5 years)

Total Project Time

The project time from the signing of a contract with the installer to being able to use your solar panels can vary from weeks to months. This includes the time spent applying for permits, setting up equipment, and integrating your system into public utility grids. Depending on the installer, the total project time can range from:

- 1/2 month
- 1 month
- 2 months
- 4 months

Warranty

A solar system is expected to work for 20-30 years. If a system fails unexpectedly during the time period covered by the warranty, the installer will repair it free of charge. Depending on the installer, the warranty can be:

- 5 years
- 15 years
- 25 years

Savings In 25 Years

This is the percent savings in electricity over 25 years with solar, compared to what you would pay your utility company without solar. This percent savings already takes into consideration the cost of installing the solar system. If the system is purchased up front, the cost is distributed over 25 years.

The savings tend to be lower with more advanced equipment and longer warranties since they are usually more expensive. However, depending on a variety of factors, such as the equipment you choose, the price the installer offers, the way you finance the project and so on, the savings can vary:

- 10%
- 25%
- 40%
- 55%
- 70%

Solar System

Imagine you have selected your solar installer. After inspecting your roof, the installer recommends several solar systems and asks you to choose the one you prefer.

As before, in the next section you will first read seven pages of information that can help you to make educated decisions when choosing solar systems. Please spend enough time on each page to read them carefully (again, the survey will not allow you to proceed if you spend too little time on each page). After that, you will be given some questions to answer.

A solar system converts sunlight into electricity. The two major components of a solar system are:

- Solar panels, which convert sunlight to direct current (DC) electricity
- Inverters, which convert the DC electricity produced by panels into alternative current (AC), which can be used directly by household appliances

Below is an example of a solar system. Explanations of each feature are on the following pages.

	Example System
Panel Efficiency	18% efficiency
Panel Visibility	High visibility
Inverter Type	Central inverter
Failures in First Five Years	2 failures
Environmental Benefits	3 acres of forest
Savings in 25 Years	40% savings

Panel Efficiency

This is the percentage of sunlight power that a panel can convert to electricity. To produce the same amount of energy, you will need fewer high-efficiency panels than low-efficiency panels.

Five options for panel efficiency:

- 15.5% (low)
- 18.0%
- 20.5% (medium)
- 23.0%
- 25.5% (high)

To produce the same amount of electricity as 18 low efficiency panels, you will need 14 medium efficiency panels, or 12 high efficiency panels. If your roof is small, you may want higher efficiency panels to fit into the limited space. High efficiency panels can also leave more roof space for system expansion in the future.

Panel Visibility On Roof

Depending on the colors and styles of the solar panels, they may be more or less visible on a roof. Here are two common scenarios:

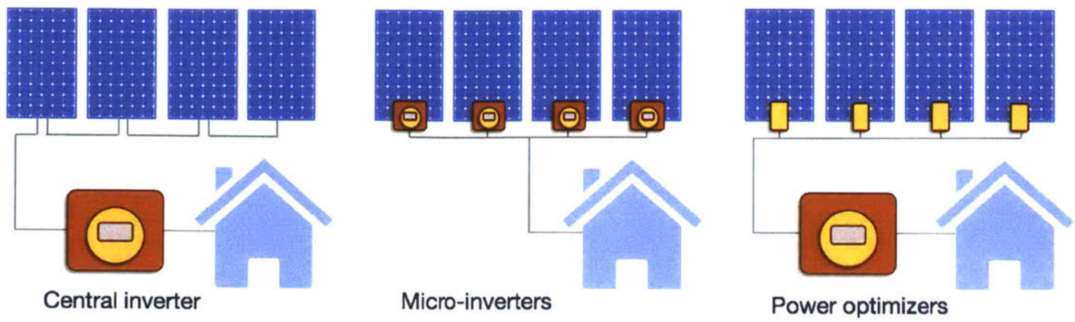
- High visibility - panels visually contrast with roof
- Low visibility - panels visually blend in with roof

Inverters

Inverters convert energy produced by solar panels into electricity that can be used directly by household appliances. There are three options for inverters:

- Central inverter - one inverter connects a group of panels
- Micro-inverter - each panel has its own inverter
- Power optimizer - a compromise between central and micro inverters. One inverter connects a group of panels but each panel has its own power optimizer.

If one solar panel in a system is broken or is shaded by a tree, a central inverter will prevent all other panels from working, while micro-inverters will allow other panels to continue operating at full power, and a power optimizer will allow other panels to keep working but with slightly lower efficiency.



Failures In First Five Years

Due to manufacturing defects and other unexpected conditions such as bad weather, a solar system may break down every so often. Different solar systems can have different numbers of failures in the first five years:

- 0 failures
- 1 failure
- 2 failures
- 3 failures

Environmental Benefits

Solar systems emit much less carbon dioxide (CO_2) when generating electricity compared to fossil fuels and thus can provide significant environmental benefits. The reduction of CO_2 emissions of a solar system each year can be converted to the equivalent area of a forest that absorbs the same amount of CO_2. Different solar systems can have different forest area equivalents from 3 to 9 acres of forest.

- 3 acres of forest
- 6 acres of forest
- 9 acres of forest

Savings In 25 Years

This is the percent savings in electricity over 25 years with solar, compared to what you would pay your utility company without solar. This percent savings already takes into consideration the cost of installing the solar system. If the system is purchased up front, the cost is distributed over 25 years.

The savings tend to be lower with higher efficiency panels and more reliable equipment since they are usually more expensive. However, depending on a variety of factors, such as the equipment you choose, the price the installer offers, the way you finance the project and so on, the savings can vary:

- 10%
- 25%
- 40%
- 55%
- 70%

Appendix C

Eco-Feedback Survey Design and Results

C.1 Resource Consumption Knowledge Questions

The knowledge questions in each of the four resources categories and their standard answers are summarized below.

Electricity

Question: What is the typical electricity consumption of the following devices?

Unit: Watt-hour (Wh)

Reference point: Running a 40-Watt light bulb for 1 hour consumes 40Wh energy.

Items for estimation (standard answer)

- Running a room air conditioner for 1 hour in summer (1000 Wh)
- Running one washing machine cycle, about 45min (500 Wh)
- Drying clothes in a dryer for one cycle, about 1h (3000 Wh)
- Using a laptop computer for 1h (40 Wh)
- Heating a glass of milk in a microwave (30 Wh)
- Running a refrigerator for 1 day (1200 Wh)

Material

Question: To the best of your knowledge, what is the most environmental friendly way to dispose of the following type of waste?

Options:

- Landfill: Dispose waste by burying it underground.
- Recycle: Convert waste into usable material.
- Compost: Decompose organic waste into fertilizer

Waste to dispose (standard answers)

- Leftover food (Compost)

- Cardboard boxes (Recycle)
- Glass bottles (Recycle)
- Plastic yogurt containers (Recycle)
- Paper milk cartons (Recycle)
- Newspaper and magazines (Recycle)
- Broken ceramics (Landfill)
- Aluminum soda cans (Recycle)
- Used batteries (Recycle)
- Banana peels (Compost)

Transportation

Question: What is the emission per person of the following modes of transportation? Assume the vehicle is half loaded and travelling a distance of 400 km or 250 miles. This is approximately the distance between Dammam and Riyadh (for Saudi Arabian respondents), or New York City and Washington DC (for US respondents).

Unit: Kilogram (kg) or pound (lb) CO_2 equivalent

Reference point: An average person breathes out 0.9kg / 2lb CO_2 per day.

Modes of transportation (standard answer)

- Car (32 kg / 70.5 lb CO_2 equivalent)
- Bus (16 kg / 35.3 lb CO_2 equivalent)
- Train (20 kg / 44.1 lb CO_2 equivalent)
- Airplane (160 kg / 352.7 lb CO_2 equivalent)

Water

Question: How much water is typically consumed by each of the following activities?

Unit: Liter (L) or gallon

Reference point: A can of Coca-Cola is approximately 1/3 L or 0.1 gallon.

Items for estimation (standard answer)

- Letting a tap run for 10 min (76 L / 20 gallon)
- Letting a tap drip, about 10 drips/min, for a day (3.6 L / 0.95 gallon)
- Flushing a standard toilet once (7.6 L / 2.0 gallon)
- Using a washing machine for 1 cleaning cycle, about 1h (120 L / 31.7 gallon)
- Using a dishwasher for 1 cleaning cycle, about 45min (30 L / 7.9 gallon)
- Taking shower for 10min (79 L / 21 gallon)

The standard answers were developed based on information from multiple online resources:

- Carbon Independence, 2015. http://www.carbonindependent.org/

- Choppin, S., 2009. Emissions By Transport Type, The Guardian. http://www.theguardian.com/environment/datablog/2009/sep/02/carbon-emissions-per-transport-type (accessed 4.21.17).
- Electrical Appliance Typical Energy Consumption Table, n.d. http://www.chabotspace.org/assets/BillsClimateLab/Electrical Appliance Typical Energy Consumption Table.pdf (accessed 4.21.17).
- Home Water Works, n.d. http://www.home-water-works.org/indoor-use (accessed 4.21.17).
- Michael Bluejay - Saving Electricity, n.d. http://michaelbluejay.com/electricity/
- Reduce, Reuse, Recycle, 2017. United States Environmental Protection Agency. https://www.epa.gov/recycle (accessed 4.21.17).

C.2 Environmental Awareness Questions

Questions asked to evaluate responses environmental awareness are listed below.
Please indicate how strongly you agree or disagree with the following statements.
(1 - Strongly Disagree, 2 - Disagree, 3 - Neutral, 4 - Agree, 5 - Strongly Agree)

- The balance of nature is very delicate and can be easily upset
- The earth has plenty of natural resources if we can just learn how to develop them (negative)
- Human beings are responsible for global warming, pollution and other environmental issues
- Humans need to change their lifestyles to address global warming, pollution and other environmental issues
- I believe that I can change my lifestyle to address global warming, pollutions and other environmental issues
- I believe that I will sacrifice my life quality if I want to live in a more environmental friendly way (negative)

How would you rate the environmental friendliness of your lifestyle?
(From 1-5, 1 is Not Environmental Friendly, 5 is Highly Environmental Friendly)

How would you rate your environmental awareness?
(From 1-5, 1 is Not Aware, 5 is Highly Aware)

C.3 Design Ratings and Most Preferred Choices

The below table summarizes the mean and standard deviation of ratings of the four criteria for each design, as well as the percentage of survey participants that chose the respective designs as their most preferred.

Table C.1: Design ratings (mean ± SD) and distributions of the most preferred choices

	Design forms	Text or Chart	Visual Emphasis	Metaphor using object	Metaphor using living creatures
Clarity Ratings	Electricity meter	3.76 ± 1.25	4.30 ± 0.79	3.43 ± 1.19	3.36 ± 1.26
	Light switch	4.20 ± 1.02	2.51 ± 1.36	2.95 ± 1.32	2.86 ± 1.28
	Paper towel dispenser	3.82 ± 1.24	4.18 ± 1.07	3.39 ± 1.30	3.68 ± 1.25
	Waste cans	4.27 ± 0.83	3.61 ± 1.12	4.05 ± 0.99	2.97 ± 1.35
	Fuel economy meter	3.68 ± 1.21	3.78 ± 1.19	3.08 ± 1.25	3.32 ± 1.24
	Public-transport poster	3.87 ± 1.03	3.65 ± 1.24	2.80 ± 1.24	3.67 ± 1.17
	Water tap	4.21 ± 1.05	3.34 ± 1.39	2.94 ± 1.31	3.49 ± 1.25
	Washing machine	3.89 ± 1.10	3.64 ± 1.31	2.57 ± 1.32	3.34 ± 1.32
Emotion Ratings	Electricity meter	2.67 ± 1.12	3.63 ± 1.00	2.67 ± 1.12	3.46 ± 1.28
	Light switch	2.89 ± 1.22	2.27 ± 1.11	3.00 ± 1.28	3.42 ± 1.30
	Paper towel dispenser	2.39 ± 1.17	3.28 ± 1.08	2.88 ± 1.19	3.66 ± 1.11
	Waste cans	2.67 ± 1.18	2.60 ± 1.08	3.15 ± 1.12	3.05 ± 1.16
	Fuel economy meter	2.75 ± 1.15	3.21 ± 1.18	2.52 ± 1.08	3.33 ± 1.12
	Public-transport poster	3.24 ± 1.19	3.25 ± 1.23	2.33 ± 1.05	3.30 ± 1.10
	Water tap	3.26 ± 1.20	3.39 ± 1.25	2.65 ± 1.18	3.79 ± 1.17
	Washing machine	2.99 ± 1.19	3.12 ± 1.24	2.74 ± 1.21	3.43 ± 1.16
Effetiveness Ratings	Electricity meter	3.40 ± 1.20	4.11 ± 0.90	2.82 ± 1.35	3.36 ± 1.31
	Light switch	3.42 ± 1.07	2.46 ± 1.21	2.85 ± 1.28	3.11 ± 1.28
	Paper towel dispenser	2.49 ± 1.15	3.35 ± 1.19	2.70 ± 1.23	3.58 ± 1.11
	Waste cans	3.91 ± 0.96	3.20 ± 1.13	3.78 ± 0.97	2.95 ± 1.22
	Fuel economy meter	3.11 ± 1.09	3.33 ± 1.13	2.77 ± 1.08	3.20 ± 1.12
	Public-transport poster	3.50 ± 1.08	3.33 ± 1.18	2.31 ± 1.08	2.95 ± 1.18
	Water tap	3.87 ± 1.09	3.43 ± 1.25	3.05 ± 1.15	3.54 ± 1.17
	Washing machine	3.68 ± 1.09	3.59 ± 1.18	2.78 ± 1.16	3.38 ± 1.25
Appeal Ratings	Electricity meter	3.17 ± 1.16	3.94 ± 0.89	2.85 ± 1.27	3.16 ± 1.35
	Light switch	3.21 ± 1.05	2.40 ± 1.15	2.85 ± 1.27	3.14 ± 1.25
	Paper towel dispenser	2.80 ± 1.07	3.40 ± 1.14	2.64 ± 1.23	3.75 ± 1.06
	Waste cans	3.47 ± 1.16	2.97 ± 1.16	3.63 ± 1.04	2.81 ± 1.25
	Fuel economy meter	3.06 ± 1.13	3.40 ± 1.17	2.58 ± 1.08	3.32 ± 1.16
	Public-transport poster	3.40 ± 1.09	3.46 ± 1.22	2.41 ± 1.05	2.88 ± 1.18
	Water tap	3.71 ± 1.13	3.12 ± 1.35	2.79 ± 1.25	3.41 ± 1.28
	Washing machine	3.27 ± 1.20	3.31 ± 1.21	2.57 ± 1.21	3.12 ± 1.26
Most preferred choices	Electricity meter	21.8%	52.8%	7.7%	17.6%
	Light switch	44.4%	14.8%	16.9%	23.9%
	Paper towel dispenser	5.8%	29.2%	9.4%	55.6%
	Waste cans	48.5%	9.4%	33.9%	8.2%
	Fuel economy meter	24.6%	42.3%	4.2%	28.9%
	Public-transport poster	38.0%	40.8%	6.3%	14.8%
	Water tap	46.3%	20.7%	8.5%	24.4%
	Washing machine	21.8%	52.8%	7.7 %	17.6%

Appendix D

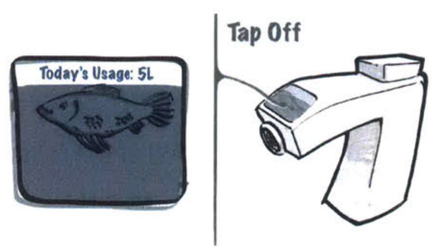
Eco-Feedback Experiment Design and Results

D.1 Example Questions in Experiment Step e)

Note: Only the sans-serif text below was the original text present in the survey. The sequence of conserving and wasteful scenarios and the order of the 15 emotions were randomized for each participant.

Product Introduction

Below is a water faucet design. It monitors the accumulated water usage of the day and displays that information on its screen. The more water is used, the lower the fish tank water level will be on the display. Imagine that your kitchen sink has a water faucet like this.



(This design was presented as GIF animation in the study)

Actionable Scenario

Imagine that you are doing dishes after dinner. You rinse all the utensils and then start to soap them. The faucet shows the fish tank water level going down on its display as below. What will you do in this scenario?

Please select your answer to complete the following sentence.

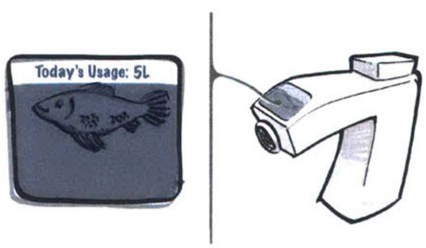
(This design was presented as GIF animation in the study)

I will _____ take the effort to turn off the faucet when soaping the dishes.

1. definitely not
2. very unlikely to
3. probably not
4. maybe
5. probably
6. very likely to
7. definitely

Conserving Scenario

Now imagine that you turned off the faucet when soaping the dishes to save water. The faucet showed the accumulated water usage on its display as in the below image after you finished. How would you feel in such a scenario?



Please indicate to what extent you would feel each of the following emotions:

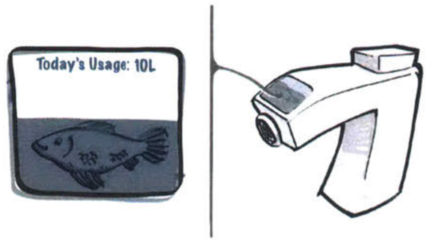
	Not at all	Slightly	Moderately	Strongly	Extremely
Annoyed	O	O	O	O	O
Guilty	O	O	O	O	O
Upset	O	O	O	O	O
Joyful	O	O	O	O	O
Surprised	O	O	O	O	O

(Rest of the 10 emotions were eliminated to save space)

Optional comments: Please write in any other emotions (and their intensity) that you would have.

Wasteful Scenario

Now imagine that you let the water run during the whole time you spent cleaning the dishes. After you finished, the faucet showed the accumulated water usage on its display as in the below image. How would you feel in such a scenario?



Please indicate to what extent you would feel each of the following emotions:

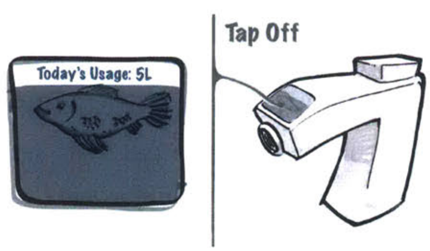
	Not at all	Slightly	Moderately	Strongly	Extremely
Interested	O	O	O	O	O
Warmhearted	O	O	O	O	O
Bored	O	O	O	O	O
Excited	O	O	O	O	O
Satisfied	O	O	O	O	O

(Rest of the 10 emotions were eliminated to save space)

Optional comments: Please write in any other emotions (and their intensity) that you would have.

Design Evaluation

How would you evaluate this water faucet design based on the following criteria?



(This design was presented as GIF animation in the study)

Aesthetics - is this design aesthetically pleasing (does it look good)?

1. Not at all aesthetically pleasing
2. Slightly aesthetically pleasing
3. Moderately aesthetically pleasing

4. Very aesthetically pleasing
5. Extremely aesthetically Pleasing

Usefulness - is this design an effective reminder to save water and would it encourage you to do so?

1. Not at all useful
2. Slightly useful
3. Moderately useful
4. Very useful
5. Extremely useful

Willingness to use - would you be willing to use this water faucet instead of a normal one?

1. Not at all willing to use
2. Slightly willing to use
3. Moderately willing to use
4. Very willing to use
5. Extremely willing to use

Overall evaluation - do you think this is a good design, all things considered?

1. This is a horrible design!
2. This is a bad design
3. This is an OK design
4. This is a good design
5. This is an awesome design!

D.2 Comparing Experimental Stage 1 and 2

The experiments were conducted in two stages: stage 1 in spring and stage 2 in summer 2018. Distributions of gender, age, and level of education of the participants in each stage and each environmental group were summarized in Table D.1.

Constrained by the pool of participants that were available at the Behavioral Research Lab, the demographic distributions were not exactly the same in the two stages of the experiment. To test if participants' age, gender and level of education were linked to their pro-environmental attitude scores and their certainty of taking conservation actions, we first ran linear regressions:

$$Y \sim Group_Q + Group_F + Age + Gender + EL2 + EL3 \tag{D.1}$$

Where Y could be either the certainty of taking conservation action with any of the four products or the pro-environmental attitude score; $Group_Q$ and $Group_F$ were dummy

Table D.1: Demographic distributions of participants within each experimental stage and experimental group

	Control Group	Quantitative Group	Figurative Group
Stage 1	-	**Total: 15** Female: 10; Male: 5 Age: 37.6 ± 15.7 EL1: 4; EL2: 7; EL3: 4	**Total: 15** Female: 9; Male: 6 Age: 35.8 ± 16.9 EL1: 3; EL2: 9; EL3: 3
Stage 2	**Total: 14** Female: 7; Male: 7 Age: 38.4 ± 10.6 EL1: 3; EL2: 6; EL3: 5	**Total: 11** Female: 4; Male: 7 Age: 38.6 ± 12.5 EL1: 2; EL2: 4; EL3: 5	**Total: 13** Female: 7; Male: 6 Age: 38.9 ± 14.1 EL1: 2; EL2: 6; EL3: 5

Note: Age distributions were reported as mean ± sd; EL stands for education level, EL1 some college or lower degree; EL2 bachelor's degree or equivalent, EL3 master or PhD degree.

variables for quantitative and figurative groups; $EL2$ and $EL3$ were dummy variables for the level of education. No significant coefficients were found for age, gender or level of education in any of these regression analyses, indicating no significant influence of the demographic factors.

Next, to test if asking pro-environmental attitude questions before evaluating the designs (step e of the experiment) had any priming effect on participants' responses to the questions of how likely they were to take actions to conserve resources, analysis of variance (ANOVA) was conducted between certainty of taking immediate resource conservation behavior in stage 1 and stage 2, for each design and within quantitative group and figurative group. In addition, ANOVA was conducted to compare the pro-environmental attitude scores between stage 1 and stage 2 participants within each of the two experimental groups. The results were summarized Table D.2. No significant differences (on 0.05 level) were detected.

Table D.2: Comparing two experimental stages with ANOVA

F-value (p-value)		**Quantitative Group**	**Figurative Group**
Certainty of Taking Immediate Resource Conservation Action	Electricity Meter	2.358 (0.138)	0.027 (0.87)
	Light Switch	0.315 (0.580)	4.179 (0.051)
	Water Faucet	1.314 (0.263)	0 (1)
	Washing Machine	1.721 (0.202)	1.18 (0.287)
Pro-Environmental Attitude Scores		0.065 (0.801)	0.340 (0.565)

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