Energy Mirror:
A Design Exploration of Physical and Ambient Visualizations for Residential Energy Consumption

by

Zeynep Irem Sismanturk

B.Sc., Middle East Technical University, 2016

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Arts

in the
School of Interactive Arts and Technology
Faculty of Communication, Art and Technology

SIMON FRASER UNIVERSITY

Summer 2022

Declaration of Committee

Name:	**Zeynep Irem Sismanturk**
Degree:	**Master of Arts**
Title:	**Energy Mirror: A Design Exploration of Physical and Ambient Visualizations for Residential Energy Consumption**
Committee:	**Chair:** Kate Hennessy Associate Professor
	Lyn Bartram Supervisor Professor, Interactive Arts and Technology
	William Odom Committee Member Associate Professor, Interactive Arts and Technology
	Gillian Russel Examiner Assistant Professor, Communication

Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

a. human research ethics approval from the Simon Fraser University Office of Research Ethics

or

b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University

or has conducted the research

c. as a co-investigator, collaborator, or research assistant in a research project approved in advance.

A copy of the approval letter has been filed with the Theses Office of the University Library at the time of submission of this thesis or project.

The original application for approval and letter of approval are filed with the relevant offices. Inquiries may be directed to those authorities.

Abstract

Existing eco-feedback designs that focus on residential energy conservation aim to create energy awareness and encourage consumers to reduce excessive use. A shortcoming that is common in many designs is the effort and time that users need to put into understanding the information presented. This project aims to increase the accessibility of information and energy awareness by making use of ambient and physical visualizations. The energy mirror design brings information into users' home environment by physically embodying the energy consumption data. The design adopts a slow technology approach by creating a consistent and gradual awareness of the users' energy consumption while also allowing instant feedback on the current power draw. The user study for the project involves interaction simulations and use scenarios with the participants where their feedback for the design was collected. The results provide insights that can be useful for future work that takes a similar approach to eco-feedback design. Specifically, the results highlight the privacy and conflict issues that may arise while attempting to increase the accessibility to the data.

Keywords: ambient visualization; physical visualization; eco-feedback design; slow technology; energy conservation; energy awareness; design-oriented research

Dedication

To my family Haluk, Tülay and Çağan Şişmantürk,

and my partner Barbaros Özyüksel,

who supported me in every way possible throughout this journey.

Thank you for believing in me.

Acknowledgements

I would like to thank my supervisor Professor Lyn Bartram for her support, guidance, compassion and patience throughout the making of this thesis. I appreciate her guidance during the design process, her financial support, and for me the most important of all: her emotional support and encouragement.

I would also like to thank Nick Tchernikov for creating the energy data simulation that was used as a part of the design prototype. I am also very grateful for his help when I struggled with programming and prototyping, for his input in the design process and his motivational support.

I am very grateful to Professor Will Odom for his advice and guidance in this research. I also want to thank Anıl Ufuk Batmaz, Barbaros Özyüksel and İrem Hocaoğulları Yılmaz for lending a hand when I needed help during this project.

Thank you to all the participants who contributed to the user study.

Lastly, I want to thank my family and partner for all their unconditional love and support. I am eternally grateful for having you in my life.

Table of Contents

Declaration of Committee ii
Ethics Statement iii
Abstract iv
Dedication v
Acknowledgements vi
Table of Contents vii
List of Tables xi
List of Figures xii
List of Acronyms xiv
Glossary xv

Chapter 1. Introduction 1
1.1. Process and Approach 3
1.1.1. Problem Definition 5
What kind of energy consumption information is useful for users to save energy? 5
Which methods of delivering energy use information are effective in terms of accessibility and awareness? 6
How can eco-feedback designs motivate users to save energy? 6
1.1.2. Ideation 7
Why ambient visualization? 7
Why physical visualizations? 8
Why slow technology? 8
1.1.3. Prototype and Testing 8
1.1.4. Anticipated Contributions 9
1.2. Methodology 9
1.2.1. Design-Oriented Research 9
1.2.2. User Study 10
1.2.3. Qualitative Analysis 11
1.3. Thesis Organization 11

Chapter 2. Background 13
2.1. Energy Consumption Effects on the Environment 13
2.1.1. Residential Energy Consumption 15
2.1.2. Factors Affecting Residential Energy Consumption 16
2.1.3. The Role of Consumers in Energy Conservation 19
2.2. Environmental Psychology and HCI 20
2.2.1. Factors Affecting Energy Use Behaviour 20
2.2.2. Knowledge 21
2.2.3. Motivation 23
Rewards/Penalties and Incentives/Disincentives 24
Goal-setting and Commitment 25
Social Impact 27

2.2.4. Feedback....30
Traditional Bills....31
Enhanced Bills and Intervention Studies....33
Web-Based Dashboards and Mobile Applications....34
In-Home Displays....37
Ambient Feedback....40
Aesthetic Visualization and Art....42
2.2.5. Behaviour....45

Chapter 3. Research Motivation and Goals....47
3.1. Design Motivation....47
3.1.1. Design Implications....47
3.1.2. Additional Methods....49
Physical Visualization....50
Slow Technology....51
3.2. Research Design....53
3.2.1. Research Goals....53
3.2.2. Research Questions....54
How would a product that visualizes residential energy consumption exist in people's home environment?....54
How would this product affect users' perception of energy consumption?....54
What kinds of consequences need to be considered when introducing energy feedback into people's daily lives?....54
What kind of design insights and improvement opportunities can be gained from this project?....55
3.2.3. Approach....55
3.3. Limitations....56

Chapter 4. Energy Mirror Design....57
4.1. Design Considerations and Decisions....57
4.2. Product Design....58
4.2.1. Energy Consumption....59
4.2.2. Current Power Draw....63
4.2.3. Smart Mirror....64
Data Visualization Display....65
Ambient Display....66
4.2.4. Mobile Application....67
4.3. The Prototype....69

Chapter 5. User Study....71
5.1. Procedure....71
5.2. Study Structure....71
5.2.1. Introductory Questions....72
5.2.2. Product Introduction....72
5.2.3. User Interaction Simulation....72

Setting up the mirror....72
User experience during daily activities in the house....72
Mirror Customizations....73
5.2.4. Follow-up Questions....73
5.3. Data Collection....73
How would the energy mirror exist in people's home environment?....74
How would this product affect users' perception of energy consumption?....74
What kind of outcomes (consequences and benefits) can be seen from introducing energy feedback into people's daily lives?....74
What kind of design insights and improvement opportunities can be gained from this project?....74
5.3.2. Semi-Structured Interviews....74
5.3.3. Video Recordings and Observations....74
5.3.4. Layout Drawings....75
5.4. Data Analysis....75
5.4.1. Pre-Study Information....76
5.4.2. Energy Mirror....76
5.4.3. Design Feedback....77
5.5. Results....77
5.5.1. Placement, Comprehension and Utility....77
Mirror Placement....77
Personal Configurations....78
Comprehension and Awareness....80
5.5.2. Outcomes of the Mirror's Presence at Home....81
Awareness....81
User Experience....83
Motivation....84
5.5.3. Potential Impact on Social Interactions....84
Conflict Between Household Members....85
Privacy Concerns....85
5.5.4. Summary of Findings....89
5.5.5. Design Implications and Redesign Insights....90
Privacy and Conflict....91
Customizations....92
Information Clarity....92
Marketing and Appeal....93
Alternative Uses....94

Chapter 6. Conclusion and Future Work....95
6.1. Contributions....96
6.2. Future Work....97

References....99

Appendix. Application Prototype....117

List of Tables

Table 5-1. Research questions and data collection methods. 74
Table 5-2. Data analysis structure. 75
Table 5-3. Summary of findings and emergent themes. 90

List of Figures

Figure 1-1. The non-linear 5 stages of design thinking (R. F. Dam, 2021). 3
Figure 1-2. The double diamond model of design thinking (J. Liu, 2016, p. 4). 4
Figure 2-1. CO_2 emission amounts of different energy resources (Nejat et al., 2015). ...14
Figure 2-2. (Left to right) (a) Energy resources used for residential consumption in 2010 (IEA, 2020a; Nejat et al., 2015). (b) Shares and percentages of CO2 emissions of the top ten countries in 2010 (IEA, 2020b; Nejat et al., 2015)....................15
Figure 2-3. Percentages of sectors in global electricity consumption (IEA, 2020). 15
Figure 2-4. Appliance electricity consumption percentages (U.S. Energy Information Administration (EIA), 2019b). 17
Figure 2-5. Average annual electricity consumption by type of home and region in 2015 (U.S. Energy Information Administration (EIA), 2019b)....................18
Figure 2-6. Electric bill examples (left to right): (a) Electricity bill in Artvin, Turkey (Gungut, 2019). (b) Electricity bill by PPL Electric Utilities in Pennsylvania, U.S. (PPL Electric Utilities, 2020). 32
Figure 2-7. BC Hydro electricity bill website dashboard (BC Hydro, 2020). 34
Figure 2-8. Mobile energy monitoring application examples (left to right): (a) HydroHome app (b) Nexia™ (c) Sense Home Energy Monitor. 36
Figure 2-9. In-home point-of-consumption and wall-mounted/countertop displays (left to right): (a) Kill-A-Watt (b) ecoMeter (c) PowerCost Monitor (d) Google Home Hub 37
Figure 2-10. Ambient energy displays (left to right): (a) Power-Aware Cord (b) Watt-I-See ambient energy source visualization (top) and power draw visualization (bottom) (c) Wattson Energy Monitor....................40
Figure 2-11. Ambient visualizations (left to right): (a) Ambient EnergyOrb (b) Ambient Canvas kitchen backsplash display. 42
Figure 2-12. Artistic visualizations (left to right, top to bottom): (a) 7000 Oaks and Counting (Holmes, 2007) (b) Aquatic Ecosystem (Froehlich et al., 2012) (c) Rainflow (Froehlich et al., 2012)....................43
Figure 3-1. Tangible visualization and interaction examples (left to right): (a) Weather Lamp prototype that physically visualizes weather data (A. Wu, 2010) (b) Time Turner prototype that visualizes family moments on calendar with coasters (Singhal et al., 2017)....................50
Figure 3-2. Initial stages of prototyping and idea generation involved tangible units and interactive design to access energy consumption data and control devices....................55
Figure 4-1. An early design concept for the energy mirror in which the frame disintegrates into the mirror to grab users' attention. 57
Figure 4-2. Energy mirror concept design....................58
Figure 4-3. Units sliding from the frame into the mirror to indicate that there has been excessive energy consumption in the room/category that the unit represents. 60

Figure 4-4. Example of how excessive consumption is calculated for the units (left to right): (a) First week's energy consumption and the daily average (b) Second week's consumption compared to the first week with excessive use highlighted. 61
Figure 4-5. Lights around the frame represent the amount of power draw in the room/category they represent with their brightness. 63
Figure 4-6. Smart mirror visualizations (left to right): (a) Customizable data visualizations (b) Ambient visualizations. 64
Figure 4-7. Energy consumption related widgets. 65
Figure 4-8. Personal and non-energy related visualizations. 65
Figure 4-9. Information summaries for rooms/categories. 66
Figure 4-10. Different customizable ambient visualization options. 67
Figure 4-11. Mobile application screens. 68
Figure 4-12. Front and back images of the mirror prototype. 70

List of Acronyms

GHG	Green House Gas
HCI	Human Computer Interaction
IHD	In-Home Display
PoC	Point of Consumption

Glossary

Ambient Display	“Ambient displays are abstract and aesthetic peripheral displays portraying non-critical information on the periphery of a user’s attention.” (Mankoff, Dey, Hsieh, Kientz, Lederer, & Ames, 2003)
Eco-feedback	“Eco-feedback technology provides feedback on individual or group behaviors with a goal of reducing environmental impact.” (Froehlich et al., 2010)
Slow Technology	“A design agenda for technology aimed at reflection and moments of mental rest rather than efficiency in performance.” (Hallnäs & Redström, 2001)
Vampire Power	“Vampire power denotes the power consumed by the devices in stand-by or during sleep mode.” (Mullai & Sivasamy, 2017)

.

Chapter 1. Introduction

As the concerns for global warming, climate change, pollution and their possible devastating effects on our planet and its inhabitants increase, efforts for achieving sustainable living conditions arise. These efforts can be seen in a variety of ways from government initiatives and countless research studies to reduce our negative impact on nature, to small individual contributions in our daily lives, as well as research studies focusing on said individual behaviours. One of the most important ways that individuals can contribute to sustainability is by managing their energy consumption. This study, among many others, also focuses on how to alter daily human activities and behaviour towards energy consumption through design to achieve sustainable living on an individual level.

One of the main aspects that are leading to global warming and climate change has been identified as energy consumption and greenhouse gas (GHG), more specifically CO_2, emissions. Currently, the majority of energy resources, namely biomass fuels, municipal solid waste, coal, and fossil fuels have a high amount of CO_2 emission rates, and modern renewable resources that have a low impact on the world such as wind, solar, geothermal, and hydropower are not used commonly enough to provide a sustainable global energy production (Nejat et al., 2015).

Although it is not the main and biggest contributor, residential activity is one of the most important factors that influence the overall energy consumption and CO_2 emissions in the world. Studies show that residential energy use encompasses around %21 of global energy consumption in 2017 (IEA, 2020a). Therefore, changes in consumer behaviour regarding energy consumption in the residential context can have a significant impact on the environment, especially in countries such as China, the US and some of the European countries that share the biggest part of the worldwide energy consumption (Nejat et al., 2015). Consequently, consumer energy awareness and behaviour are crucial components of maintaining environmental sustainability and ensuring the safety of future generations of living beings inhabiting our planet.

We use energy in many aspects of our daily lives. Many of our activities, whether they are essential or arbitrary, are tied to products consuming energy. Although some of our energy use is necessary to maintain our living standards, some of this energy consumption is unnecessarily wasted. Research suggests that even the smallest changes in our daily activities such as turning off unused products and efficiently using heating and cooling devices can add up to a significant amount of savings as a society (R. Woodbury et al., 2008). People that have the awareness of the environmental issues and are willing to make an effort for this cause or people who are just aiming to reduce their electricity bills are trying to reduce this waste. However, do they really know how to reach an ideal energy consumption without any waste? Are they aware of what product uses the most energy, and how they can efficiently reach their goal of sustainability? What determines the necessity and non-negotiability of some of these activities? These questions are highly important for users' decision-making processes, therefore filling this gap of information could have a significant contribution to a sustainable living environment.

Many studies are focusing on consumer behaviour regarding energy use, trying to understand what motivates people to conserve energy and make an effort toward sustainable living, as well as research studies that work on and test the methods of persuasive design to influence consumers to be mindful and efficient of their daily energy use. With the help of technology and design, it becomes possible to not only inform the users and guide their decisions regarding their energy consumption, but also show the impact of their actions on the environment, which is argued to be an important factor that motivates users to reduce their consumption.

This study was inspired and informed by, built on, and combined the knowledge and design implications acquired by related studies including HCI and environmental psychology research. Several design decisions were based on the findings of such studies and aim to challenge the effectiveness of suggested design implications as well as explore novel methods of eco-feedback for informing household residents. These related research studies will be discussed in the background section, giving appropriate context to the motivation behind the design of the eco-feedback prototype that this thesis presents.

1.1. Process and Approach

The process of this project relies on the 5 stages of design thinking suggested by the Hasso-Plattner Institute of Design at Stanford, also known as d.school (Meinel et al., 2011a). Design thinking is a human-centred design methodology that aims to solve complex and hard to define problems. This method challenges the designers to look

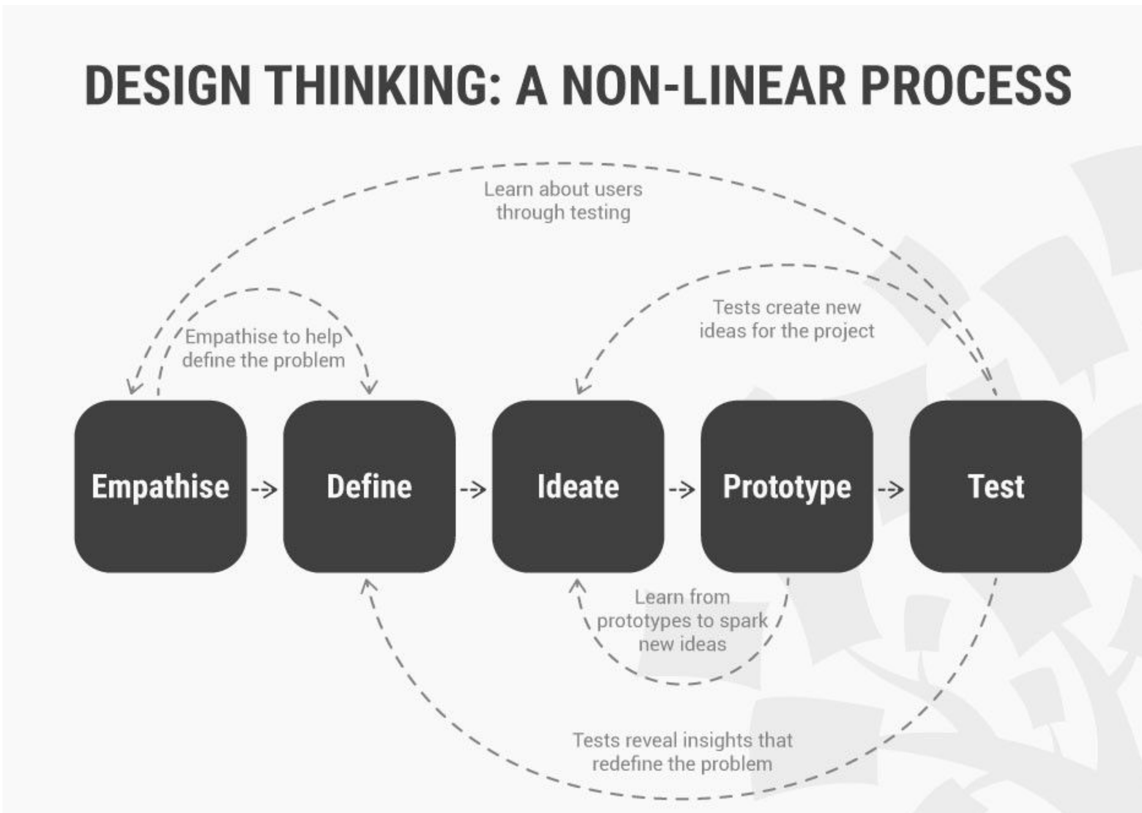


Figure 1-1. The non-linear 5 stages of design thinking (R. F. Dam, 2021).

from the user's point of view, understand their desires and needs, and question their own assumptions in order to create a solution that prioritizes human needs. The 5 stages of this process are *Empathize*, *Define*, *Ideate*, *Prototype* and *Test (*Figure 1-1*)*. While in theory the process seems to consist of simple linear steps, in reality the process is actually more complex and not always sequential. Depending on the project, the steps may require the designer to go back to other stages and redefine the problem or be inspired by the prototype to ideate new designs.

In the *Empathize* stage, the designers use various ways to understand the users, their needs and problems, research the existing solutions and identify their strengths and shortcomings from the consumer's perspective. This provides the designers with the ability to see outside of their design and production priorities so that the outcome of the projects are first and foremost user-centred solutions. In this stage, to discover the right problem(s) to solve, the designers use a divergent thinking process (Figure 1-2) to cover as many sources and areas related to the topic as possible. It is a beneficial method to discover issues that the designer might not have experienced or observed.

In the *Define* stage, the designers then converge on the ideas and considerations in the previous stage and analyze the observations and insights to solidify a problem statement for the project. The problem definition is used as a starting point for the idea generation process. However, depending on the later stages of the project the designers may need to come back to this stage to redefine the main problem that the project aims to solve.

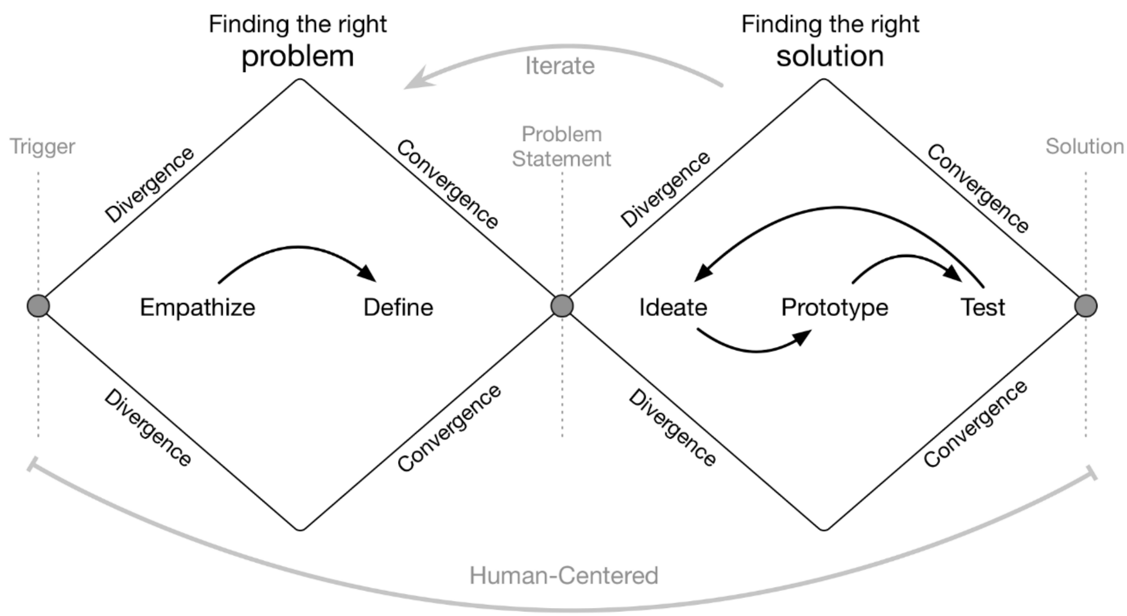


Figure 1-2. The double diamond model of design thinking (J. Liu, 2016, p. 4).

The *Ideation* stage is where the brainstorming and designing take place. The designers diverge again to iterate as many ideas as possible. There are numerous techniques of idea generation including sketching, brainstorming, prototyping, role-playing and storyboarding. The goal at this stage is to come up with lots of different and/or innovative ideas, even if they are not necessarily realistic, so that there are enough options to gather inspiration from and narrow down the final design.

In the *Prototype* stage, the designers converge on the ideas from the previous stage and use inexpensive and/or easily acquired materials to build low-fidelity prototypes. These are helpful to understand if the design works as intended and see the opportunities or constraints in the design. This stage can be useful both for further idea generation and refining or improving the design.

Finally in the *Test* stage, the design prototypes are tested by users either in controlled or real-life situations to see if the goal of the project is achieved and the defined problem is successfully solved. As with the other stages, the process might require the designers to go back to the ideation and prototyping stages, or it might even be necessary to go all the way back to research and redefine the problem.

1.1.1. Problem Definition

For this project, the literature review and product research are a part of the *Empathize* stage, which is covered in the *Background* section of this thesis. The existing design solutions for sustainable residential energy consumption are researched so that their strengths and weaknesses, as well as the opportunities for new ideas and technologies, are discovered. Furthermore, in order to better understand energy-related user psychology, the literature review of various user studies related to the topic provides an insight into the users' perspectives and needs.

In light of this research, the problem area is identified as a part of the *Define* stage. The main goal of the project is to design a product that encourages the users to reduce unnecessary energy consumption at home. Some questions arise following this research:

What kind of energy consumption information is useful for users to save energy?

In order to save energy in their homes, users need to acquire some knowledge to act on, such as how much energy different kinds of devices in their homes consume, what kind of activities use more energy and how they can alter their habits to achieve energy conservation. It is necessary to distinguish what kind of information is important to show for the purpose of conserving energy and which ones are unnecessary, irrelevant or would cause the users to be overwhelmed. There are also different ways of presenting information which can affect how useful and influential it is for the users. Highlighting different aspects might produce various effects, which can also differ for each person. This project aims to explore what kind of information might be important for users, the different ways of informing them and giving feedback about their own energy consumption, as well as questioning the effectiveness of these methods.

Which methods of delivering energy use information are effective in terms of accessibility and awareness?

One of the main problems of commonly used methods of eco-feedback is that it takes time and effort to easily access and understand the energy use information, which is a significant factor that discourages users from investigating their data. Furthermore, the information seldom attracts users' attention for it to be worth their effort and time. For that reason, it is important to eliminate this factor so that the information is easily accessible and interesting. This accessibility provides increased awareness of users' energy consumption, both for the consumption in the present moment and for their cumulative energy use during a period of time.

Previous design works and user studies in the field uncover some insights into what users find interesting and how they react to at-a-glance and ambient visualizations (Darby, 2010; Quintal et al., 2016; Rodgers & Bartram, 2011). Specifically, this project aims to explore visualizations that can be seamlessly integrated into people's living environment at home.

How can eco-feedback designs motivate users to save energy?

Without the motivation to save energy, the product will fail to encourage sustainable behaviour by simply informing the users about their energy consumption. Therefore, it is important to have a sufficient source of motivation for the users. A significant part of the motivation depends on the users' personal values and ideals, however, it can also be affected by external factors. There might be some motivational aspects as well as the knowledge perspective on how the information is presented. For instance, the impact on nature might be motivational for one person, but guilt-inducing and negative for another (Rodgers & Bartram, 2011). This project aims to find out what kind of external factors might be effective and how can they be implemented in the product design. Mainly, the design aims to motivate users by providing constant awareness of energy consumption by fitting the feedback into the home environment. The visualizations are used to inform the users while also straying away from scolding the users and making use of neutral and positive motivators.

Combining these design questions together results in the main question that this project aims to address: *'What are the design implications for an ambient eco-feedback product that visualizes energy consumption in the house?"*

1.1.2. Ideation

Following the problem definition, several ideas that aim to address the aforementioned design questions are explored for the *Ideate* stage. Previous design works have inspired and informed the design decisions in this process to solve the problem of excessive energy consumption in the home. There are a few key components to the eco-feedback design in this project. The primary approach is to adopt ambient visualizations as the main method of informing the users. Secondly, it explores the concept of physical visualizations in the eco-feedback context. Lastly, the product is designed to be a slow technology that encourages gradual behavioural change regarding energy consumption.

The idea generation process is partially simultaneous with the *Empathize* and *Prototype* stages. It is necessary for the project to carry the idea generation while doing further research, and also experimenting with the ideas through prototyping. The ideation process also includes brainstorming and sketching as a way to come up with multiple distinct solutions.

Why ambient visualization?

One important aspect that drives the design is the goal of exploring how eco-feedback can be integrated into daily life and products in the house. The main approach for achieving this goal is to utilize ambient visualizations with products that are involved in users' daily routines. This design decision allows the information to be comprehensible at-a-glance, meaning that it can take less time and effort to gather relevant information to save energy without being overwhelmed with the details and eliminating the barrier of having to perform an action to access the data. It also keeps the users constantly aware of their energy use, allowing it to influence in-the-moment decisions regarding activities that involve energy consumption.

Why physical visualizations?

As a way to better integrate the energy consumption data into people's lives at home, the design makes use of physical visualizations accompanied by a standard digital energy tracking application. Compared to digital visualizations, physical visualizations have the opportunity of existing in the living environment even if the product seems "offline". Considering that energy is an abstract concept, physically visualizing it can bring the users' attention to the issue of unnecessary consumption. It is used with the goal of mimicking a more natural representation of the data so that people can instinctively comprehend the big picture (Moere & Patel, 2009; Zhao & Moere, 2008). Moreover, it is a feature that can lower the knowledge barrier and allow children to get familiar with the concept of energy consumption earlier and learn how much activities and habits have an impact on it. Consequently, this knowledge can reach beyond the electricity bills that the parents pay.

Why slow technology?

Saving energy is a slow process that does not provide instant overnight results. It requires users to be patient and to slowly but surely adjust their habits in order to adopt more sustainable behaviours. The slow technology aspect of the design represents the realistic process of achieving that goal over a long period of time. This approach aims to create interactions with the product that allows the users time to contemplate and reflect on their actions (Grosse-Hering et al., 2013; Hallnäs & Redström, 2001; W. Odom, Banks, et al., 2012). The subtle and slow changes in the visualizations also aim to encourage gradual behavioural change, much like how high-impact diets are ineffective in the long term while gaining sustainable and healthy eating habits can last for a lifetime.

1.1.3. Prototype and Testing

The design makes use of a mirror and its frame as a way to inform users about their energy consumption and encourage sustainable behaviour. During and after the *Ideate* stage, low fidelity prototypes with cardboards and foamboards are utilized to refine the product design. Finally, a higher fidelity prototype is built to be used as a part of the user study.

The user study represents the *Test* stage of the design process. It consists of an interview and interaction simulation to explore the possible outcomes of the design existing in a home environment. During the user interaction simulation, users are presented with the design and are asked to imagine scenarios that explore various forms of interaction possibilities. The testing process aims to discover what kinds of implications different methods can offer and what improvements can be made to further the design.

1.1.4. Anticipated Contributions

As a result of the testing process, this project aims to contribute to a better understanding of the implications of bringing energy consumption data into people's home environments and daily lives. The implications that are anticipated include how this product may affect users' perception of energy consumption, as well as its effects on their lives, routines and relationships. With these implications, designers can keep important considerations in mind while further exploring this concept.

1.2. Methodology

In this research study, the objective is to use design, prototyping and user testing as a research tool to understand user psychology and build on design implications regarding energy consumption feedback in the residential context. This project also involves a user study that is mainly based on observation, semi-structured interviews and use scenarios. As a result, this project is based on design-oriented research using qualitative methods.

1.2.1. Design-Oriented Research

Fallman (2007) makes a distinction between the projects in the HCI field according to their primary objective.

> "To briefly introduce these two notions, one can see design-oriented research – where research is the area and design the means – as a

> conduct that seeks to produce new knowledge by involving typical design activities in the research process. In this paper, a design component or element is used to drive and propel research.
>
> In research-oriented design, however – where on the contrary design is the area and research the means – the creation of new products and, in that process, answering to the problems and real-world obstacles that are faced in that process, is the primary objective."

With respect to this distinction, the project could be separated into two parts in which design and research are respectively prioritized. In the first half of this project, research is used as a guide and inspiration to design the energy mirror, which is considered as research-oriented design. Whereas in the second half, the product is tested and used as a means to further the research by revealing new design knowledge, and therefore it is design-oriented research. However, the ultimate goal of the project is to contribute to the betterment of eco-feedback designs in the residential context, so the project overall prioritizes research instead of the production of a design artifact. Therefore, this project takes a design-oriented research approach. As such, the product design in this project serves as a research tool rather than a refined design to be manufactured.

1.2.2. User Study

A user study was conducted using the prototype of the product design in order to test and get user feedback. Kosara et al. (2003) indicate that user studies are crucial to highlight the strengths and weaknesses of visualization designs and provide an opportunity to test their utility. The user study in this research involves adaptive semi-structured interviews and use scenarios to achieve more natural and elaborate responses from the participants.

As a part of the user study, the User Enactment method was utilized. In user enactments, participants are presented with the physical form of the design in the spatial and social context (which is as close to the reality as possible) to provide a simulated real-life experience (W. Odom, Zimmerman, et al., 2012). The users are then asked to participate in loosely scripted scenarios and their behaviours and expressions are observed. With this method, the participants imagine themselves in possible use scenarios and interact with the design. This allows the researchers to explore the possible interactions and situations in the simulated context so that the participants can provide more realistic responses and interactions. In the context of this project, the user enactment aims to engage the users in the imaginary future situations with the energy mirror design in the context of their home environment in order to discover actions, feelings and opinions that may otherwise be obscure.

1.2.3. Qualitative Analysis

The core research question aims to investigate the complex relationships between people and their use and perception of energy consumption at home. The main objective of the user study is to gather insights into the users' opinions and their interaction patterns with the prototype rather than to measure the effectiveness of the energy mirror on the actual energy consumption values. Considering the variables of the context, cultural and historical background of the participants, the research methods require an adaptive process rather than straightforward quantitative measures, which might be more useful for identifying and understanding the cause-and-effect relationships between factors and therefore possibly inadequate for the complexity of the problem (Creswell, 2007). Thus, the user study structure and analysis in this project adopt a qualitative approach.

1.3. Thesis Organization

This thesis document consists of the following six chapters:

Chapter 1: Introduction gives a summary of the topic, the problem area and what this thesis project aims to achieve, as well as describing the research and design process and presenting the thesis structure.

Chapter 2: Background covers the literature review of the problem and existing product designs and research studies on this topic. The problem definition starts with the effects of worldwide energy consumption on the environment and converges into individual energy use habits, highlighting the importance of the fact that energy savings in the residential context can affect the overall environmental impact. Then, the previous methods and designs that aim to influence sustainable behaviours are examined from the perspective of environmental psychology.

Chapter 3: Research Motivation and Goals begins by explaining the design implications that are motivated by the literature review. The product design aims to make use of the strengths of previous works while introducing new approaches, such as slow technology and physical visualizations. This chapter also presents the research goals and questions that the user study aims to address. Lastly, the limitations of the project and user study are addressed.

Chapter 4: Energy Mirror Design demonstrates the design process, the details of the final product design and the prototype built for the user study. The energy mirror design focuses mainly on ambient eco-feedback and motivating sustainable behaviour through physical and digital visualizations.

Chapter 5: User Study includes the details of the structure and results of the user study. The study consists of a user interaction simulation and intends to understand the users' perspectives, opinions and how the design may affect their daily lives at home. Along with the effectiveness of the visualizations on user comprehension and motivation, various concepts such as privacy, household relationships and daily habits are examined. The study takes a design-oriented research perspective and its results are analyzed using qualitative methods. The design implications based on the research results are also discussed in this chapter.

Chapter 6: Conclusion and Future Work gives a summary of the insights and findings of this thesis research. This section discusses the contribution of the thesis to the sustainable design field and suggests possible future work that might be inspired by this project.

Chapter 2. Background

2.1. Energy Consumption Effects on the Environment

GHG emissions, and more specifically carbon emissions are the most dominant and significant contributors to global warming. What were once hypotheses and future scenarios of several studies in the past can be seen in the current events as a result of global warming. For instance, increased flooding cases in Malaysia, droughts in Australia and Africa, intense summer heatwaves in Europe, melting glaciers and rising sea levels in the arctic poles, as well as climate change and extreme weather events all around the world (Yau & Hasbi, 2013). Humans have a crucial impact on the state of nature due to their activities. As more countries continue to develop and due to the population increase all around the globe every year, the production and consumption rates of energy increase accordingly, further aggravating the greenhouse effect. According to Enerdata's Global Energy Trends report, global energy consumption increased by 2.2% in 2018, and 0.6% in 2019 as compared to the previous years (Enerdata, 2020). Although Ritchie and Roser (2015) argue that there isn't a clear correlation between economic growth and energy consumption and that the link between these topics is not always unidirectional, some research studies provide evidence suggesting the opposite, presenting the idea that economical growth in a country results in increased energy consumption. As an example, a study by Auffhammer and Wolfram (2014) demonstrates that residents' incomes play a significant role in the number of energy-consuming products they acquire and use in China. Furthermore, residents in developing countries tend to own and use more personal appliances, thus causing an increase in residential energy consumption (IEA, 2008).

Energy consumption plays a crucial role in global GHG emissions. Energy use around the world requires resources for production, and as the demand increases over time due to developing industries and the increase in power-consuming products, the use of these resources escalates accordingly. The main reason for the damage energy consumption inflicts on the environment can be traced back to its production. Although growth in energy production using nuclear and modern renewable sources, such as solar, wind, geothermal and hydropower, can be seen in some countries (Nejat et al., 2015), the majority of the sources that are still used have a significant contribution to

Energy source	kg CO_2 per mmBtu
Coal coke	113.67
Municipal solid waste	90.70
Biomass fuels (solid)	
Agricultural byproducts	118.17
Peat	111.84
Solid byproducts	105.51
Wood and wood residuals	93.80
Natural gas	53.06
Oil products	
Kerosene	75.20
Liquefied petroleum gases (LPG)	61.71
Crude oil	74.54
Biomass fuels (liquid)	
Vegetable oil	81.55
Ethanol	68.44
Biodiesel	73.84
Electricity (kg CO_2 per kW h)	0.624

Figure 2-1. CO_2 emission amounts of different energy resources (Nejat et al., 2015).

CO_2 emissions. A comparison of these energy sources demonstrates that coal and biomass, followed by municipal solid waste and oil have the highest emission factor among all the sources used for energy production (Figure 2-1). In fact, fossil fuels consisting of coal, oil and natural gas are responsible for 80% of global energy utilization (Suganthi & Samuel, 2012). Considering the fact that biomass and waste share the biggest portion (39.7% in 2010) of energy sources used in residential energy consumption (Figure 2-2**Error! Reference source not found.**a), residential energy use c an be consequently tied to environmental issues, and changes in the household behaviour have the potential to decrease the carbon footprint of the human race.

Sustainability efforts in some countries are especially more important, due to their high share in worldwide energy consumption. Figure 2-2**Error! Reference source n ot found.**b demonstrates the worldwide CO_2 emission percentages of countries in 2010, and studies show that the top ten major contributors include China, the United States, Russia, India, Japan, the United Kingdom, Korea, Germany, Iran and Canada (Nejat et al., 2015). These countries have the highest potential to influence CO_2 emissions and reduce our carbon footprint by mitigating energy consumption levels.

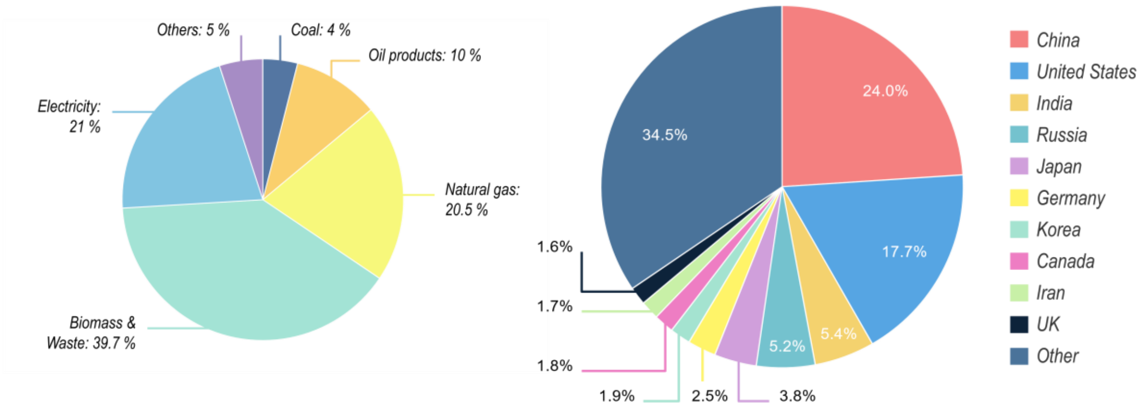


Figure 2-2. (Left to right) (a) Energy resources used for residential consumption in 2010 (IEA, 2020a; Nejat et al., 2015). (b) Shares and percentages of CO2 emissions of the top ten countries in 2010 (IEA, 2020b; Nejat et al., 2015).

2.1.1. Residential Energy Consumption

As demonstrated in Figure 2-3**Error! Reference source not found.**, followed b y the industry (~42%), residential electricity consumption is the third biggest sector that affects global electricity use, constituting around 27% of the total around the world (IEA, 2020b). This information further supports the idea that energy savings in the residential sector can influence GHG emissions, and therefore, global warming and climate change.

Not only does energy consumption affect climate change, but also climate change influences energy consumption decisions in return. As global warming causes

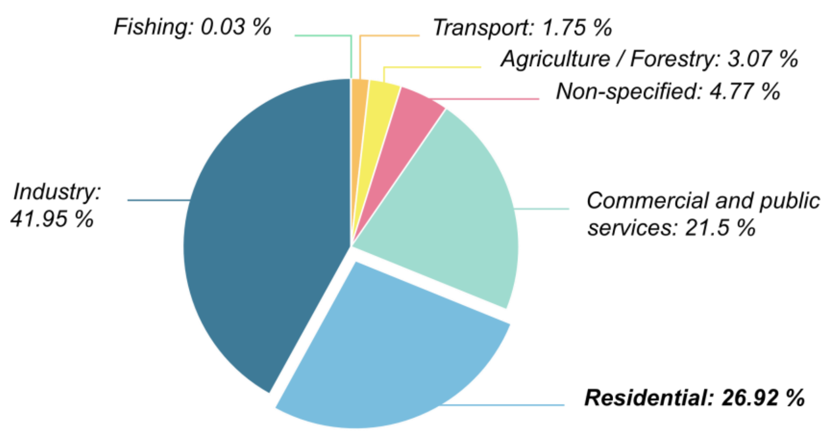


Figure 2-3. Percentages of sectors in global electricity consumption (IEA, 2020).

higher heat levels in the summer seasons, the use of air-conditioning devices increases accordingly. Likewise, the winters would be warmer, thus requiring lesser heating needs. A European study shows that in some northern countries the decrease in electricity demands for heating would be higher than the increase in cooling needs, while in others, namely southern European countries, the opposite would likely occur (Li et al., 2012). In the major energy-consuming countries like the US and China, a similar change of use patterns would likely be seen with the temperature management appliances. Therefore, depending on the geological location, global warming and climate change are issues that continue to feed themselves through residential energy consumption habits.

2.1.2. Factors Affecting Residential Energy Consumption

There are many considerations that determine and affect energy use in a household. These could be categorized into *contextual* and *individual* factors.

Contextual factors consist of aspects that surround the living environment of individuals. Some of these are factors that affect the energy consumption in the house more *directly* than others. U.S. Energy Information Administration (2019a) provides a list of such factors including the following:

- **Geological location of the house:** The location of the house determines the climate and weather conditions that influence the temperature management devices in the house. Weather conditions also determine how much users spend time at home, thus using devices during that time.

- **The physical characteristics of the house:** Several aspects of the house can have an effect on the energy consumption in the house from the material choices that influence the house insulation, to the size of the space that requires to be heated or illuminated. It takes more time and energy to heat up a larger house, so energy consumption is consequently higher than in smaller homes. Furthermore, the type of the house also affects the insulation, meaning that apartments that are insulated by adjacent apartments are generally more insulated than the detached houses, resulting in up to nearly three times less energy used to heat up the house (U.S. Energy Information Administration (EIA), 2019a). Figure

2-5 shows that while apartments in the Northeast U.S. used the least amount of electricity in 2015, detached houses in the South consumed the most electricity annually.

- **The number and characteristics of the appliances used in the house:** Naturally, the number of appliances will have an effect on the overall energy consumption. The type and energy efficiency of these products is also an important aspect. Temperature and air management appliances are major contributors to electricity consumption in homes (U.S. Energy Information Administration (EIA), 2019b). The three biggest categories that consume the most energy can be identified as air conditioning (17%), space heating (15%) and water heating (14%) (**Error! Reference source not found.**).

  There has been major growth in the use of air conditioning in the United States. A comparison between 1980 and 2015 demonstrates an increase from 57% to 87% of homes using air conditioning (U.S. Energy Information Administration (EIA), 2019b). On the other hand, how often and how long the household members use the energy-consuming products is a crucial consideration as well, however, this is determined partly by the behavioural factors which will be discussed later.

- **Number of household members:** Typically, the more members a household has, the more energy consumption is likely to occur. This factor can also be directly connected to the type and size of the house.

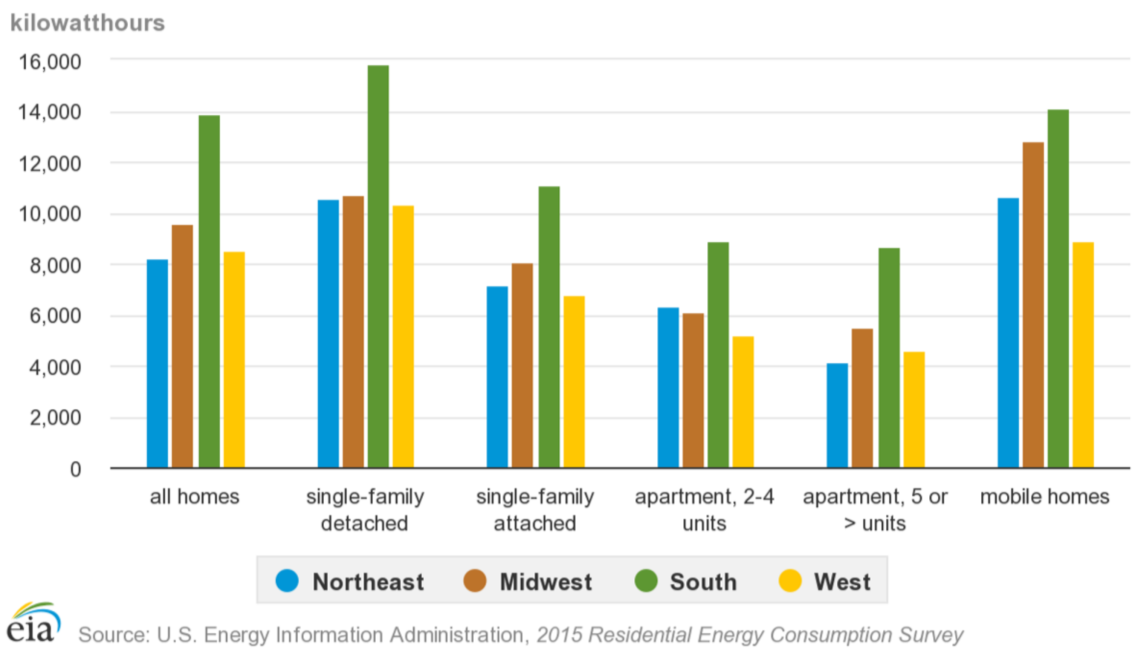


Figure 2-4. Average annual electricity consumption by type of home and region in 2015 (U.S. Energy Information Administration (EIA), 2019b).

Another factor of consideration is standby power or what researchers call the *vampire power* draw. Some of the appliances in users' homes have standby or sleep modes in which they continue to consume energy even though it is considerably low. However, the accumulated amount of many of these low energy-consuming devices results in 5% to 10% of household energy consumption and 1% of global CO_2 emissions (Mullai & Sivasamy, 2017; Ross & Meier, 2001). Research suggests that devices that have the largest vampire draw are home entertainment systems (e.g. television, stereo system, video game console, cable box), printers, microwaves, computers or laptops and chargers (Meier & Nordman, 2008).

On the other hand, there are also contextual factors that *indirectly* influence energy consumption, as well as more complex considerations that are related to individual behaviour. Abrahamse et al. (2005) identify these as macro-level factors, also referred to as "TEDIC factors: technological developments (e.g. energy-intensive appliances), economic growth (e.g. increase of household incomes), demographic factors (e.g. population growth), institutional factors (e.g. governmental policies) and cultural developments (e.g. emancipation, increasing mobility of women)", a term referenced from Gatersleben and Vlek (1998). The availability and accessibility of energy-efficient alternatives, the current infrastructure and economic factors are important determinants of people's product purchase decisions. In addition, there are also external persuasive forces that come into play in people's lives, which affect their behaviour. Some of the examples include intervention strategies by designers or the government, social pressure, and advertising (Bartram et al., 2011; Stern & Dietz, 1994).

2.1.3. The Role of Consumers in Energy Conservation

There are multiple ways of attempting to mitigate the gas emissions caused by residential energy consumption, some of which are out of the users' control. These sustainability efforts include energy policies that are put in place by the government, such as financial incentives towards more energy-efficient solutions, namely tax incentives and benefits, grants and subsidies, investment in modern renewable energy sources and discouraging the use of environmentally damaging energy sources like fuel, biomass and coal (Nejat et al., 2015; Pablo-Romero et al., 2017). Likewise, the decisions of designers and engineers also play a crucial role while producing energy-efficient and sustainable products to ensure minimal damage to the environment. The choice of materials, how much resource a product consumes during its use, or how it influences users' energy-related activities and habits are contributing aspects that the designers and engineers can control to a certain point. It is important to consider if the product encourages sustainable behaviour or promotes unnecessary energy use (Holmes, 2007).

On the other hand, the daily actions of consumers are proven to have a significant impact on residential energy consumption by up to 50% (Schipper et al., 1989). Even small actions like turning off the lights, reducing heating or changing the washer setting can amount to energy savings between 10% to 20%, and thus a meaningful change with the combined effort of a community of households (R. Woodbury et al., 2008). However, consumers are mostly unaware of how much energy they use or how their individual actions actually impact the environment. Although some of the household members might have a general sense of how to reduce energy consumption, designers have the opportunity to provide the necessary and accurate information. Still, simply providing relevant data is not enough to engage the users, so designers should also consider the motivators that influence the users to save energy (Bartram, 2015).

2.2. Environmental Psychology and HCI

2.2.1. Factors Affecting Energy Use Behaviour

What determines a user's energy consumption habits is an important yet complicated topic. While we can't simply list all the factors that come into play, many studies have attempted to understand the motivations and behavioural patterns of consumers.

Aside from the aforementioned contextual factors that influence energy consumption, Abrahamse et al. (2005) also mention some of the micro-level, individual factors that affect energy use. Depending on people's living environment and the macro-level factors (e.g. their country, culture, family, friends or education), different individual factors are established (e.g. opportunities, motivations, emotional states, ideals, relationships) and each person develops their own *values, norms, beliefs* and *attitudes*. These individual factors are highly dependent on the contextual aspects, and it is important to recognize this link while understanding people's skills, knowledge and motivations (Strengers, 2011).

Personal factors play a role in how people perform *actions*, acquire *habits* and *routines*, thus their behaviours naturally affect how they use energy-consuming products. We can give many examples of varying energy use habits that are the results of these factors, such as people celebrating Christmas using lights to decorate their homes or arranging family gatherings at home (for which they prepare food, clean the house or entertain guests, actions which all use energy different than daily use) (beliefs and traditions), socially active people who like to regularly organize gatherings at home (habits and routines), or even children who form a habit of turning off the lights they don't use just to avoid scolding from their parents but not because of their own decisions (social pressure).

Based on the framework of Steg (2008) and Darby (2010), we can recognize these factors as contributors to the consumers' *knowledge, motivation, awareness* and *behaviour* toward energy conservation. Users need to gain *knowledge* about the nuances of energy consumption, be familiar with their own energy consumption through *eco-feedback*, have a reliable source of *motivation* to conserve energy - that is effective and will last a long time - and as a result, implement their knowledge into energy-saving *behaviour*.

2.2.2. Knowledge

An essential part of energy conservation primarily requires knowledge of the issue and how to eliminate it. Nowadays, many people are generally aware of the environmental issues and their ties to energy consumption (though the technical details of how and why are still not considered as common knowledge (Bord et al., 2000)), yet an insufficient part of the population is conscious of the fact that individual behaviour change can actually have a significant impact on the environment.

Most people are not familiar with energy-related terminology and the link between consumption, cost and environmental impact (Strengers, 2011). In addition, there are many misconceptions about which appliances or behaviours use more energy. According to Schuitema and Steg (2005), while some people relate size to the energy consumption of a product (which is not always proportionate), they also underestimate the energy required for heating water. People also perceive the act of turning off the unused lights as one of the most important ways of conserving energy (probably due to its high visibility), even though lights consume considerably low energy compared to heating or cooling appliances (Strengers, 2011). Another example is that people usually tend to overestimate big events such as social events or holidays, or high-level effects such as temperature or weather, believing them to be the most crucial factor while ignoring the effect of daily routine activities (Neustaedter et al., 2013). According to the study by Neustaedter et al., in some cases, the highest amount of consumption turns out to be in the unexpected periods of time where these factors do not have a major effect. For instance, one participant in their study was surprised that their highest consumption was in April, and another participant expected January to be their highest but instead, it turned out to be July.

Education, culture and personal interests play an important part in shaping individuals' knowledge about this information. That said, product design can also contribute to improving awareness and knowledge. Feedback and advice are proven by several studies to be effective for achieving increased knowledge. In particular, advice and information tailored specifically for each household tend to yield even more effective results (Abrahamse et al., 2005).

An important issue of users gaining knowledge is accessibility to information. While the internet provides all the information needed on this topic, consumers rarely get curious or research on their own. It is demonstrated that curiosity and interest are crucial motivators for consumers to gain knowledge about the issue and contribute to the solution (Quintal et al., 2016). Generalized information through workshops, mass media campaigns and recommended behaviour modelling, while useful to some extent, proved to be ineffective on its own for altering energy behaviour in the long term (Abrahamse et al., 2005). Another issue of accessibility is the comprehensibility of information. Since many people may not be knowledgeable about energy-related terms and data, it can be confusing and hard to understand the information presented. That is why the information should appeal to every person, provide actionable knowledge and attract the attention and interest of the consumers regardless of their education level, profession or age.

Understanding which appliances use the most energy and what behaviours and habits can impact consumption creates actionable knowledge that is crucial for energy consumption decisions. Bills usually inform about the aggregated consumption data, so they generally don’t provide information that can be directly linked to daily activities. There are a few methods for this that can be seen in the literature, one of which is to give written or verbal energy savings advice to users through the bills or other means. However, Darby (2010) suggests that there is insufficient evidence that generalized written advice has impacted energy consumption. Darby argues that while the study by Gaskell et al. (1982) resulted in electricity savings of 22% after giving users advice leaflets, the weekly visits and meter readings possibly inadvertently affected the results. On the other hand, Darby mentions that verbal advice has been found to be more effective than written (New Perspectives/Energy Inform, 2004, as cited in Darby, 2010). The reason for this outcome is presumed to be the ability to identify, discuss and find solutions to the specific problem of each household. Abrahamse et al. (2005) also support this idea, suggesting that information tailored to the needs of each household is shown to be more effective than generalized information.

Providing information is suggested to be more influential when used in combination with other strategies (Abrahamse et al., 2005). Information combined with a clear understanding of users' own energy consumption (feedback) and strong motivation will allow users to make educated decisions in their daily consumption routines and conservation efforts.

2.2.3. Motivation

People have different attitudes towards energy use. Energy is not necessarily directly consumed, but consumption is rather an outcome of people's daily activities and product use (Bartram, 2015; Holmes, 2007). While some people only prioritize comfort and time during these activities, others consider energy consumption and conservation as well. People need to have a solid motivation to conserve energy, otherwise simply presenting information and feedback will rarely achieve expected results, unless the information itself motivates the users. The reverse is also accurate, that motivation on its own is not enough to translate into behaviour without the knowledge and feedback of energy consumption (Kantola et al., 1983). The motivation for conserving energy differs for each person, their driving force could be financial savings, environmental concerns, social pressure or other reasons.

The aforementioned contextual and individual factors also impact people's motivation. For instance, people who are more educated and concerned about environmental issues are more prone to making eco-friendly decisions. Conversely, people who do not typically view their electricity bills, due to self-assigned rules of certain households or a lack of interest in the topic, are unaware of their own consumption and therefore less motivated to save energy (Chetty et al., 2009; Neustaedter et al., 2013; Strengers, 2011). The habits, roles and relationships in a household thus affect the pro-environmental motivation of users. Another example is that people, who grew up in a low-income household, would form a habit of avoiding unnecessary expenses, and therefore would be inclined to make price-driven decisions later in their lives.

As a result, understanding the types of motivations that influence energy consumption is an important step for designing products that target these motivations and encourage sustainable behaviour. Bartram (2015) emphasizes the different effects extrinsic and intrinsic motivations have on voluntary behaviour change. It is argued that extrinsic motivations, such as financial rewards or consequences, are less reliable and consistent than intrinsic motivations that are rooted in personal and internal values (e.g. saving energy for altruistic and environmental reasons). Although people saving energy for environmental concerns have the highest potential to retain their sustainable habits and behaviours, it is important to keep other motivations in mind when designing for encouraging people to save energy.

It is equally necessary to understand the difference between *positive* and *negative* motivations and how they affect consumer psychology. While positive motivators, such as financial incentives, encourage the users to conserve energy by rewarding the energy-saving behaviour; the negative disincentives, like showing the damaging impact on the environment, aim to sway users away from excessive consumption (Bartram, 2015). However, negative discouragements might consequently result in negative feelings, such as guilt, dissatisfaction and shame, and eventually, users tend to disregard or get rid of designs involving these negative motivators (Rodgers & Bartram, 2011). Thus, these designs become ineffective for promoting a change of behaviour.

As a part of intervention strategies, many researchers have studied the environmental motivators and methods of encouraging users towards energy conservation. Abrahamse et al. (2005) categorized several intervention studies according to the antecedent and consequence strategies they implemented. Antecedent strategies were aimed to motivate the users *before* the energy consumption behaviour. These include information and modelling (these strategies were discussed in the *Knowledge* section), commitment and goal setting. Consequence strategies on the other hand were identified as rewards and feedback (the latter of which will be discussed in detail in the *Feedback* section). In addition to their categorization, the following section also includes the effects of social pressure and comparison on consumer motivation.

Rewards/Penalties and Incentives/Disincentives

Though they are similar in concept, rewards and penalties are separate motivators from incentives and disincentives. While incentives and disincentives are antecedent motivators, rewards or penalties are regarded as consequence motivation methods (Froehlich et al., 2010). Both categories have similar motivational aspects, including financial, environmental, social, convenience and so on.

As mentioned before, extrinsic and intrinsic motivations are seen in literature as different ways of rewarding sustainable behaviour. Financial motivators are one of the most common ways of inciting motivation for conservation. Even though these are shown to be impactful, they are also proven to be effective only while they last or are relevant to the users (Abrahamse et al., 2005; Holmes, 2007). Besides, for some people, comfort can be a more overpowering factor than pricing (Darby, 2010). This implies the need for other long-term and reliable motivations to be established.

Gratification and self-satisfaction of conserving for the benefit of the environment and humanity, on the other hand, are suggested to be a stronger and more persistent source of motivation (Bartram, 2015; Quintal et al., 2016). While they might be mostly relevant to those who are concerned with environmental issues, showing the positive effects of energy conservation on the environment is an effective method to encourage energy savings motivation. Besides, it could also attract the interest of people who are not already concerned about the environment, and by making them aware of their impact, it can incite a new motivation for them. In addition, social approval and praise can also be a rewarding motivation and could be greatly effective.

Penalties or disincentives on the other hand can also impact energy use behaviour, though they generally cause negative feelings or thoughts to occur, as discussed before. Consequently, people try to avoid negativity in their lives, leading them to withdraw from, discard or “turn off” designs that use these motivation techniques (Bartram, 2015).

Even though eco-feedback designs can not make use of financial incentives, other rewarding features can be useful to motivate users, such as game-like rewards, self-satisfaction or social acknowledgement of environmentally positive behaviour (Froehlich et al., 2010).

Goal-setting and Commitment

Goal-setting is a beneficial way to solidify a person’s intent and helps for keeping track of one’s progress. Setting a goal and committing are fundamentally interconnected and are commonly used in combination which is indicated to be a useful method of encouraging sustainable behaviour (Katzev & Johnson, 1983).

The proportion of a goal significantly impacts users' energy consumption results. While a more difficult goal can push users to try harder to save energy (Froehlich et al., 2010; Locke & Latham, 2002), it should also avoid being unrealistic. An unattainable goal can be seen as not worth the effort, it can cause frustration and therefore might become ineffective (D. Huang et al., 2016). Becker's (1978) experiment to give participants either a 20% or 2% reduction in electricity use produced critically different energy conservation results. The participants receiving the difficult goal, as well as feedback on their progress, saved 15.1% of electricity, while the group with a lower goal didn't achieve any significant results. The effectiveness of combining goal-setting and feedback is also confirmed by the studies of McCalley and Midden (2002) and van Houwelingen and van Raaij (1989).

Goals can either be set by individuals or be determined by external forces. The results of either method can differ for each person and their own motivations (Froehlich et al., 2012). For example, McCalley and Midden (2002) analyzed the correlation between self-set or assigned goals and the social value orientation of participants. It turned out that people who valued the outcome for others than themselves (pro-social) performed better with assigned goals than self-set goals, and the reverse was true for people with pro-self values.

Aside from personal set goals, we must also consider the shared goals of a household or community. In those cases, accountability, social pressure and responsibility also start to shape the motivations of individuals. Thus, shared goals were found to be effective for energy use reduction, especially when combined with rewards (Slavin et al., 1981), though there are some examples showing no significant difference between shared and individual goals (e.g. Abrahamse et al., 2007). Shared goals can also lead to discussion, information exchange and social encouragement. Staats et al. (2004) demonstrate the positive effects group discussion and feedback comparison had on energy conservation.

Research has revealed that commitment is a highly effective method for motivating people to reach a goal, arguably more than financial incentives (Holmes, 2007). According to this view, expressing an intention increases the probability of that person's success in achieving that goal (Froehlich et al., 2010). Katzev and Johnson's (1983) study is an example that supports this view, as their participants saved critically higher energy compared to people who were exposed to monetary incentives or questionnaires.

In particular, public commitments and pledges have been shown to be more impactful on consumers' motivation and conservation behaviour than private commitments. Holmes (2007) suggests that public recognition of good behaviour is a strong motivator for consumers to conserve energy. On the other hand, private pledges could be useful for people who are fundamentally driven by intrinsic motivations and moral obligations (Abrahamse et al., 2005).

The study of Pallak and Cummings (1976) is an example that shows the difference between the effects of a public and private commitment. Since the names of the participants in the public group were expected to appear in the newspaper, they felt the pressure of social (dis)approval according to their results and therefore put more effort into conserving energy as compared to the private commitment group. When it comes to public commitment, social interactions and commitment work together as a motivator.

Social Impact

Humans are fundamentally social beings. Concepts of social approval, comparison and interaction can influence the decisions of individuals drastically. There are multiple aspects of social influence that affect energy conservation motivation.

Considering others and future generations of humanity and aiming to ensure their safety and health is a part of social motivation. Some people are motivated to act in accordance with pro-environmental behaviour in order to achieve this. These people are acknowledged as pro-social and considered to be influenced by intrinsic motivators (Froehlich et al., 2010). The norm activation model assumes that people who are primarily motivated by subjective norms such as moral obligation perform altruistic behaviour even to the point of sacrificing personal gains, namely cost, time and effort (Schwartz, 1977). Feelings associated with pride or guilt are prominent as a result of their environmental behaviour.

Other key social aspects are approval, acknowledgement, accountability and social pressure. Social approval is a consideration that some people decide and act according to depending on their costs and benefits. Minimizing cost and maximizing benefits is considered to be the main goal of behaviours and attitudes, and this is suggested to apply to environmental behaviour as well (Froehlich et al., 2010). People generally tend to consider socially approved behaviours and would be encouraged to adopt environmentally positive practices given that their actions are acknowledged and praised (Geller, 2002). Conversely, they would avoid behaviours that are frowned upon and considered shameful or inconsiderate.

Social popularity plays a significant role in how people behave and make energy consumption-related decisions, due to the perception of status and people's desire to belong in a certain social group. Nowadays pro-environmental behaviour and sustainability are seen as positive behaviour, popular and even fashionable, and have started to gain an increase of acceptance among society as the awareness of global warming and climate change has escalated over time (The Nielsen Company, 2018). Moreover, as smart objects and homes similarly started to become popular, people who tend to acquire them increased respectively (Statista Research Department, 2020). This allows designs to make use of data gathering provided by smart meters, which was not easily achievable in the past years.

An example of social impact is a study by Odom et al. (2008) which examines the behaviour and perspective of dormitory residents regarding energy consumption. For this target population, financial incentives are not applicable, so the researchers analyzed other methods to motivate consumers. They set up a pledge wall where the residents can publicly commit to saving energy. Their findings show that social incentives play a significant role in their decisions, including investigating energy consumption-related information. They found out that people were hesitant to participate in the Energy Challenge mostly because they thought "*No one else was competing so there didn't seem to be a point*." Therefore, their suggestion to attract the dormitory residents' interest was to incorporate social interaction more into their design by creating a pledge wall that serves as social comparison and competition. By pledging to conservation behaviour, students will essentially commit to a public goal and would be motivated to keep their pledge, especially when their conservation behaviour is publicly praised or "received credit". This idea could be applied to other target populations as well, by making use of people's perception of social status and respect, and their determination to keep their promises.

Social comparison also has the possibility to influence consumers' decisions and motivations. If people realize they have been consuming more than their neighbours or similar households (geographic or demographic neighbours (Froehlich et al., 2012)), they might be motivated to change their behaviour. The downside of this is when their consumption is lower than others, in which case people might increase their energy consumption (Fischer, 2008). Another use of comparison could be to create a competitive environment and reward the energy conservation behaviour of users (in any type of way, from monetary rewards to simply the satisfaction of being a winner). Competition can include a playfulness aspect to energy conservation and motivate users further. Studies examining the effect of competition resulted in notable energy savings compared to baseline amounts. For instance, an energy-saving competition among dormitory residents at Oberlin College, with the addition of eco-feedback provided, resulted in an estimated 32 percent of electricity reduction (J. E. Petersen et al., 2007). Another similar dormitory experiment at the Indiana University Bloomington campus led to an estimated 33.008 kWh of energy savings (W. Odom et al., 2008). However, while friendly competition might be motivational for some people and keeps the members accountable for each other, others might find it harmful to their relationships, especially within the members of a single household (Froehlich et al., 2012). In those cases, cooperation might be a better method instead of competition. They also note that accountability can also lead to blaming and conflict, thus it is clear that these methods are not suitable for every household.

Discussion about energy consumption-related topics can induce a motivation shift for consumers. As mentioned before, not all members of a household are aware of their energy consumption, or even the utility bill amounts (Chetty et al., 2009; Neustaedter et al., 2013; Strengers, 2011). Sharing this information, discussing conservation tips and advice with other people, encouraging each other or debating different ways to contribute to the environment can substantially change people's perspectives and motivate them to make pro-environmental decisions (Geller, 2002; Rodgers & Bartram, 2011). Designs that support household communication and social interaction are assumed to have a higher chance of raising mutual awareness (Barreto et al., 2013).

2.2.4. Feedback

Researchers have revealed that one of the most effective ways to achieve consumer energy awareness is through eco-feedback. It is based on the assumption that people are not sufficiently aware of their own energy consumption and which actions in their daily lives affect the results (Froehlich et al., 2010). Several studies since the 1970s have demonstrated the positive effects eco-feedback has on energy conservation efforts (e.g. Kohlenberg et al., 1976). Receiving information about energy use has been shown to reduce consumption from 3 to 15 percent (Darby, 2008). Although this is a very promising result, the eco-feedback methods are not at their highest potential. It is shown through studies that after the initial curiosity and exploration phase, the effects diminish over time, reducing the decrease in consumption to 3 to 4 percent (Allcott & Rogers, 2014; Ehrhardt-Martinez et al., 2010). Furthermore, one of the main concerns is that the commercially available eco-feedback services have been demonstrated to be insufficiently comprehensible for many users, and the perceived benefit and impact of users' behaviour did not justify the effort and time spent to understand the information (Bartram, 2015).

Froehlich et al. (2012) identify and examine four different design dimensions for eco-feedback: data and time granularity, comparison and measurement unit.

Data granularity determines the scale of the data: from small-scale such as consumption data on an individual fixture level, to large-scale data including the energy use of the whole city. Feedback can display the energy consumption in the whole house, rooms of the house, each appliance, categories of appliances, and so on, and each way can have a different effect on consumers.

Time granularity signifies the time period in which the data is collected and displayed. For instance, energy consumption in a day, a week or a month can be provided as feedback. Each view is suggested to present different information and usage patterns.

Froehlich et al. establish three types of comparison: self-comparison, goal-comparison and social comparison. The motivational effects of these different types of comparison were discussed in the *Motivation* section.

Lastly, they discuss the different measurement units that could be used to communicate the information. While technical terms are accurate and useful, they also explore equivalent, metaphorical and financial units as well. While their study focuses on water consumption which is a tangible resource, they mention that metaphorical and equivalent measurement units might be more useful for invisible resources such as electricity.

Many eco-feedback designs have differentiating design dimensions, some of them utilizing multiple options. Researchers argue that having multiple options in an eco-feedback design has better results and influence since many people have different preferences and motivations (Fischer, 2008; Froehlich et al., 2010).

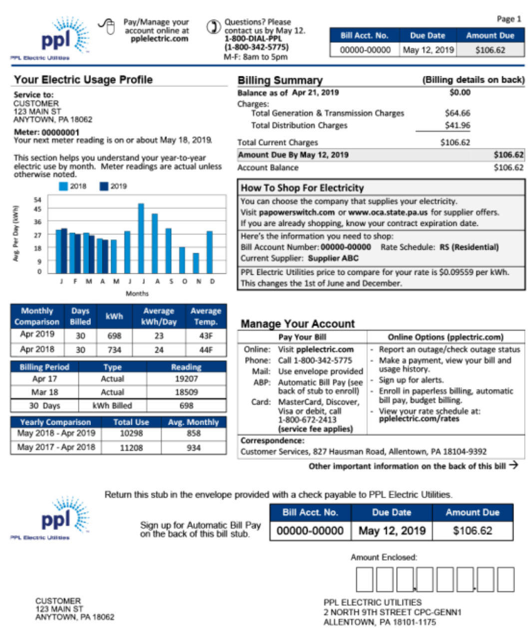
Regularly mentioned issues of eco-feedback designs consist of comprehensibility, at-a-glance awareness, accessibility, cost of effort and time, aesthetic properties and integration into users' daily lives. There exist several studies on how to improve on these issues of eco-feedback services and devices, not only for electricity use but also for natural gas and water consumption, that employ multiple methods and strategies. The following sections present the examples of eco-feedback services and devices, strategies and visualization studies; discuss their results and implications, as well as their strengths and shortcomings.

Traditional Bills

The most common type of eco-feedback for energy consumption that is widely used around the world is utility bills. These bills have a wide range of variety in terms of the information that they provide, the frequency in which they arrive and their way of delivery. The frequency can change from once every six months, bimonthly, monthly or - with the possibilities that technology and internet provide - it can even allow the users to access their daily and hourly consumption (though, web-based or other feedback types that offer hourly consumption will be discussed later). The information presented in the bill can also differ substantially. While simple bill formats only give information about the total amount of electricity used and the total cost that needs to be paid, some examples can provide basic bar graph visualizations of monthly usage, or even in some cases, detailed daily consumption as well as comparisons to weather, community average or previous year's data.

Research has disclosed that users find it hard to comprehend the eco-feedback in the form of a traditional bill, making it hard for them to know if they are consuming too much energy, be aware of how their activities affect their energy consumption and make informed decisions about how to reduce their energy use (Darby, 2010; Gaskell et al., 1982). It is proven that using visualizations is an effective way of informing the users in a way that takes less time and effort to interpret the data (Bartram, 2015; Darby, 2008; Ehrhardt-Martinez et al., 2010). Furthermore, simply providing numerical data in measurement units that are not commonly used by the general public (e.g., kWh, CO_2) is harder for the general public to make sense of (Bartram, 2015; Neustaedter et al., 2013).

The traditional paper bill used widely in Turkey (Figure 2-6a) is an example of a bill that provides information in a manner that seldom attracts users' curiosity or attention. Although some of the necessary information, such as a comparison to the last month, the total amount of energy used in both kWh and ₺ amount is included in the bill, it takes time, effort and interest to dissect and understand the data. In most cases, users simply view the total amount that they need to pay and sometimes compare it to the last month's bill payment.


ppl
PPL Electric Utilities

Pay/Manage your account online at **pplelectric.com**

Questions? Please contact us by May 12. **1-800-DIAL-PPL (1-800-342-5775)** M-F: 8am to 5pm

Page 1

Bill Acct. No.	Due Date	Amount Due
00000-00000	May 12, 2019	$106.62

Your Electric Usage Profile

Service to:
CUSTOMER
123 MAIN ST
ANYTOWN, PA 18062

Meter: 00000001
Your next meter reading is on or about May 18, 2019.

This section helps you understand your year-to-year electric use by month. Meter readings are actual unless otherwise noted.

2018 2019
Avg. Per Day (kWh)
54 45 36 27 18 9 0
J F M A M J J A S O N D
Months

Monthly Comparison	Days Billed	kWh	Average kWh/Day	Average Temp.
Apr 2019	30	698	23	43F
Apr 2018	30	734	24	44F

Billing Period	Type	Reading
Apr 17	Actual	19207
Mar 18	Actual	18509
30 Days	kWh Billed	698

Yearly Comparison	Total Use	Avg. Monthly
May 2018 - Apr 2019	10298	858
May 2017 - Apr 2018	11208	934

Billing Summary (Billing details on back)

Balance as of Apr 21, 2019	$0.00	
Charges:		
Total Generation & Transmission Charges	$64.66	
Total Distribution Charges	$41.96	
Total Current Charges	$106.62	
Amount Due By May 12, 2019		**$106.62**
Account Balance		$106.62

How To Shop For Electricity
You can choose the company that supplies your electricity.
Visit **papowerswitch.com** or **www.oca.state.pa.us** for supplier offers.
If you are already shopping, know your contract expiration date.
Here's the information you need to shop:
Bill Account Number: **00000-00000** Rate Schedule: **RS (Residential)**
Current Supplier: **Supplier ABC**
PPL Electric Utilities price to compare for your rate is $0.09559 per kWh.
This changes the 1st of June and December.

Manage Your Account

Pay Your Bill	Online Options (pplectric.com)
Online: Visit **pplelectric.com** Phone: Call 1-800-342-5775 Mail: Use envelope provided ABP: Automatic Bill Pay (see back of stub to enroll) Card: MasterCard, Discover, Visa or debit, call 1-800-672-2413 **(service fee applies)**	- Report an outage/check outage status - Make a payment, view your bill and usage history. - Sign up for alerts. - Enroll in paperless billing, automatic bill pay, budget billing. - View your rate schedule at: **pplelectric.com/rates**

Correspondence:
Customer Services, 827 Hausman Road, Allentown, PA 18104-9392

Other important information on the back of this bill →

Return this stub in the envelope provided with a check payable to PPL Electric Utilities.

ppl
PPL Electric Utilities

Sign up for Automatic Bill Pay on the back of this bill stub.

Bill Acct. No.	Due Date	Amount Due
00000-00000	May 12, 2019	$106.62

Amount Enclosed:

CUSTOMER
123 MAIN ST
ANYTOWN, PA 18062

PPL ELECTRIC UTILITIES
2 NORTH 9TH STREET CPC-GENN1
ALLENTOWN, PA 18101-1175

Figure 2-5. Electric bill examples (left to right): (a) Electricity bill in Artvin, Turkey (Gungut, 2019). (b) Electricity bill by PPL Electric Utilities in Pennsylvania, U.S. (PPL Electric Utilities, 2020).

In comparison, the PPL Electric Utilities bill from the U.S. (Figure 2-6b) provides a more user-friendly layout design that not only delivers numerical data in a more organized way, but also demonstrates the energy consumption comparison between the months using a bar graph. By highlighting the relevant and important information via contrast in size, position and colour of the graphical elements, it leads the users to the useful data in a more successful way in comparison to the previous example. However, it is still arguable that all this information is easily comprehensible and interesting for the users or that it provides sufficient information that guides the users to save energy.

This comparison between the two traditional bills demonstrates that there are multiple ways of delivering energy consumption data to the users, with wide-ranging success. The main issue that needs to be addressed with eco-feedback is that energy consumption data is neither easily understandable nor engaging to many users, which prevents them from understanding and mitigating their excessive energy use (Bartram, 2015).

Enhanced Bills and Intervention Studies

Many researchers work on strategies that aim to reduce consumption by enhancing the bill in different ways. An important problem of the current eco-feedback system is the low frequency in which the bills are delivered to customers (Gaskell et al., 1982). One of the strategies is to tackle this problem by increasing the billing frequency, which has been suggested to improve the link between daily activities and energy consumption data. This attempt has resulted in energy savings of up to 10%, which was the highest rate recorded in Norway (Wilhite & Ling, 1995).

Enhancing or altering the way information is provided through bills is another method to increase comprehensibility and awareness. According to a study done by Midden et al (1983), energy savings of up to 13% compared to the control group have been found after giving users weekly information about their usage in kWh, the % of difference compared to the reference point, financial consequences of increase or reduction, and visualizations of energy consumption. However, it is important to note that the participants were also given energy savings advice and even financial incentives, and it was a small-scale and short-duration experiment (Darby, 2010).

Web-Based Dashboards and Mobile Applications

Throughout the decades that people used electricity, the commonly used method of bill delivery used to be by paper mail, however, as the access to the internet and familiarity with digital devices increased, online services have started to become the new normal in developed countries. Unlike the traditional bills, this type of feedback grants the possibility of interaction with personal energy consumption data. Therefore, the ability to dive deeper into the energy consumption data becomes possible, while accessing and understanding the more recent energy use data becomes relatively easier. Studies suggest that the most effective feedback designs include multiple viewing options, high update frequency, comparisons, and interaction (Fischer, 2008; Froehlich et al., 2012).

As an example of web-based feedback designs, Figure 2-7 demonstrates the online billing system of BC Hydro, which is the electricity distributor in British Columbia, Canada. Their website enables users to view yearly, monthly or daily consumption visualizations as well as providing multiple comparisons, displaying predicted future use

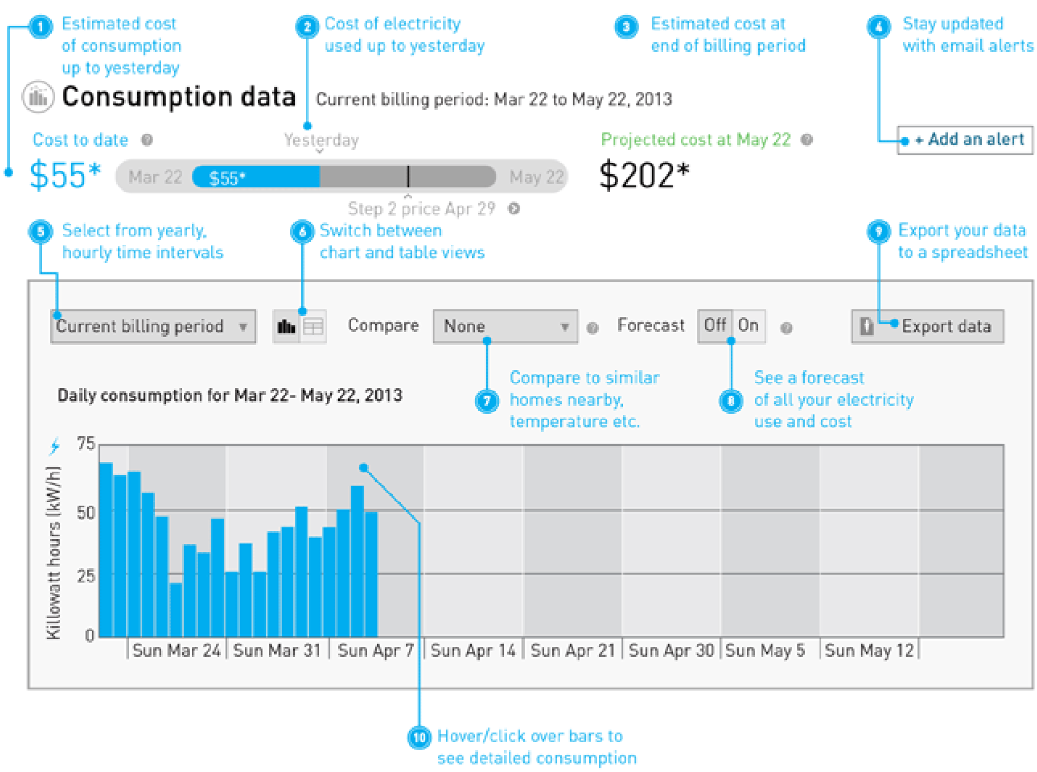


Figure 2-6. BC Hydro electricity bill website dashboard (BC Hydro, 2020).

and cost. Furthermore, users have the ability to access the website at any time, so the feedback frequency is very high compared to the standard billing system.

Similar to the traditional bills, the comprehensibility of numerical data on its own is low for the users in the web-based displays. However, the intractability of the websites and the multiple visualizations of the dashboards allow an increased comprehensibility at-a-glance, thus they are easier and more accessible for non-experts to investigate their energy consumption data. Visualization methods commonly used for energy consumption usually consist of bar charts, line graphs and pie charts. The Interactability of the visualizations is useful for making comparisons (either internal or external) and understanding correlations.

Although web-based displays provide in-depth information and frequent feedback, they still require users' effort and time to log into the website, investigate and understand the information. Excluding energy enthusiasts, many people tend to check their consumption data on the web when they receive a high bill, and rarely out of curiosity (Darby, 2010). And even then, their motivation is usually to check if the bill is correct, rather than to understand what activities and appliances caused the high consumption (Ersson & Pyrko, 2009; Neustaedter et al., 2013).

In addition to the websites created by the electricity providers to their customers, there also exist independent eco-feedback website services. Microsoft Hohm™ and Google PowerMeter™ are some of the examples that are designed to help users keep track of their electricity use at their homes using smart meters (Google.org, 2011; Ryon, 2009). However, at the time of their release, the problem with these external services was that they relied on customers to have awareness of the existence of this industry and opt into these services, so both PowerMeter and Hohm have been discontinued due to the lack of customer interest in 2011 (Korosec, 2011; LaMonica, 2011). At the time, PowerMeter and Hohm were argued to be "too early" (Fehrenbacher, 2011a, 2011b) since smart metering, smart objects and home electricity management systems were not as prevalent as they are today. In contrast, due to the current increase of interest in smart homes and objects (Statista Research Department, 2020), products and services have a higher chance of success and customer interest today.

Similar to web-based dashboards, there are mobile applications that are designed for energy monitoring. They also utilize visualization dashboards and are argued to be more ubiquitous and accessible since users can carry the device with them anywhere, even though they still have to open the application to view the information (Bartram, 2015; Ehrhardt-Martinez et al., 2010). There are many commercially available mobile application examples currently in use or in the trial stage such as Nexia™, Sense Home Energy Monitor and HydroHome (Figure 2-8). These not only allow users to view their data but they can also be used for remotely controlling appliances in one place, setting timers and schedules for appliances, getting alerts, notifications and tips about consumption and so on.

To avoid the extra effort and time required to log in to the website or launch the app, it is also possible to combine the visualizations with applications or tools that people use daily. A study by Huang et al. (2016) examined the idea of integrating data into other tools that users regularly view and use, namely personal digital calendars. The link between daily routines and collected data is crucial for energy conservation, yet research demonstrates that people find it hard to understand the connection clearly (Neustaedter et al., 2013). This study aimed to make this link more transparent so that users can understand the context behind the result and thus make informed decisions in the future. Their field study focused on fitness data on calendars, however, they suggest that the same idea can be applied to energy consumption as well. They observed emotional response, engagement and reminiscence as a result of people viewing,

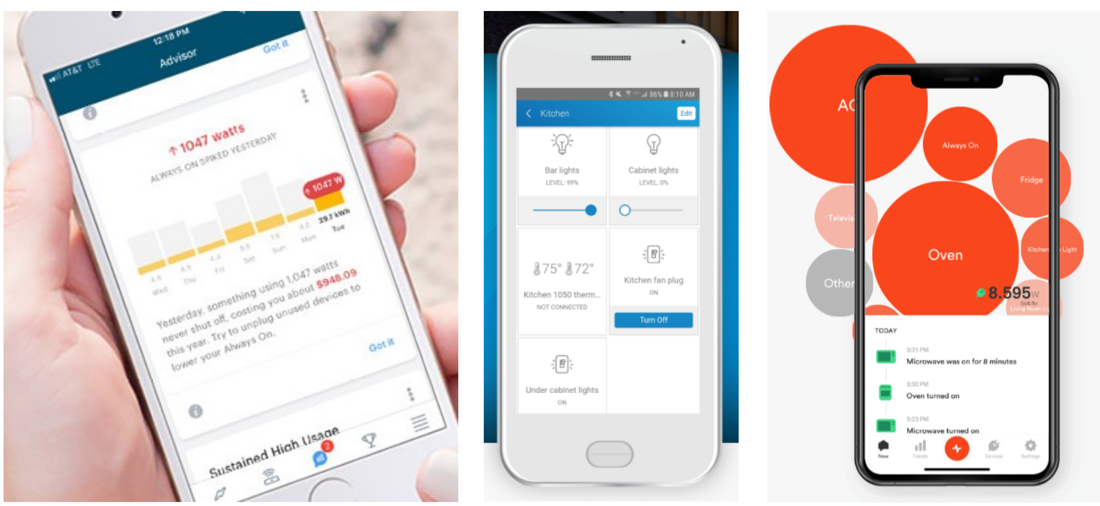


Figure 2-7. Mobile energy monitoring application examples (left to right): (a) HydroHome app (b) Nexia™ (c) Sense Home Energy Monitor.

reasoning and reflecting on the data about their past, which could provide an enjoyable experience and motivation to save energy. At the same time, they also observed that the participants did not log every single activity they perform on their calendars since people's lives are much more complex than simplified schedules and are prone to change a lot depending on the person, which limited the context for understanding the fitness data. Overall, their results are indicative that getting regular feedback via a tool that they use in their daily lives and connecting energy consumption data as closely as possible to their behaviours and habits can make it easier for users to understand the link between their actions and energy use.

In-Home Displays

While software, websites and applications require users to put effort into logging in and spending time to investigate their data, in-home displays (IHD) have the advantage of being easily accessible to customers in their own living space. These displays use smart metering and can either be a point-of-consumption (PoC) device on a single fixture, or a centralized device that displays the energy consumption throughout the house. Some of the designs only show numerical data whereas others additionally include visualizations or dashboards.

Examples of the PoC designs include Kill-A-Watt (Figure 2-9a) and other similar commercially available smart meters. Their advantage is that the link between the appliance, activity and consumption is immediate and clear (Bartram, 2015; Quintal et al., 2016; Sun, 2014). These aim to not only highlight the amount of energy each of the individual appliances consumes but also point out the vampire power draws during the

Figure 2-8. In-home point-of-consumption and wall-mounted/countertop displays (left to right): (a) Kill-A-Watt (b) ecoMeter (c) PowerCost Monitor (d) Google Home Hub

standby modes (Rodgers & Bartram, 2011). There are also designs that contain alerts for overload or cumulative data (Darby, 2010). Some of the ambient designs such as Power-Aware Cord and Watt-I-See are also a part of PoC displays (see *Ambient Feedback*).

Despite their advantage of providing real-time information or creating an awareness of how much energy appliances consume, they can become misleading and distract the users away from the appliances or outlets that use low but steady amounts of energy which eventually accumulate and significantly impact the overall result. For example, participants using EcoPioneer misunderstood spikes in data and assumed that some appliances (e.g. kettles, hairdryers, etc.), which are not used for extended periods of time, consumed more electricity than the other more ubiquitous appliances (fridge, freezer, etc.) which are in use most of the time but did not cause a spike in consumption, therefore were often overlooked (Strengers, 2011). Similarly, upon seeing the low amounts on the displays, users can feel approval and encouragement (e.g. green or orange light in EcoPioneer as opposed to 'screaming' red lights) to use these appliances more often or longer, thus resulting in higher energy consumption in some cases. Furthermore, the location of PoC displays is an important consideration. Devices like Kill-A-Watt need to be plugged into an outlet, which might not always be visible or accessible for users.

Wall-mounted or countertop energy monitoring displays, on the other hand, offer more general and in-depth data on energy consumption in the house. While the more basic designs display numerical values (e.g. PowerCost Monitor, ecoMeter) sometimes accompanied by simple bar charts (Figure 2-9b&c), since the effectiveness of visualization was proven by several research studies, most of the recent designs employ visualization dashboards for quicker viewing and sensemaking (e.g. Google Home Hub, Figure 2-9d).

Trials using the PowerCost Monitor have resulted in various outcomes, from negligibly small effects to 22% savings (Mountain, 2007). Among these studies, one that had the largest participant inclusion and a 2-year duration resulted in 4.5% (people who used the display between 1-24 months) to 6.7% (people who still used the display after two years) savings compared to the control group (Rossini, 2009). In light of these results, it has been argued that the percentage of savings is related to the duration of display use. Though, many studies show that there is a drop in interest and savings after some time (S. S. van Dam et al., 2010).

In addition to the results of energy savings, research studies also provide user reactions, habit changes and preferences regarding IHDs. One study demonstrated that users expressed feelings of “frustration, despondency and anxiety” as a result of IHDs and also highlighted the importance of the aesthetic appeal of the product (fitting in with the house environment and decor) and household member dynamics and relationships (Hargreaves et al., 2010). Interestingly, participants in another study found the in-home display PowerPlayer motivating, mentioning that it “functioned as a coach” (UC Partners, 2009, as cited in Darby, 2010). Studies also show that some people do not prefer single, centralized displays to view and control energy consumption, but rather favour distributed information and control throughout their homes (Makonin et al., 2013; Rodgers & Bartram, 2010). Simple and straightforward visualizations are also more appreciated than displays that cause information overload (Rodgers & Bartram, 2010).

Despite requiring less effort to gain information compared to the previous methods and being located in the living spaces of users, these feedback designs don’t necessarily support instantaneous understanding of data and still require a bit of an investigation. Users may still need to look at their data, compare it to other information or their goal and try to understand at which point they used energy unnecessarily. Furthermore, even though the general assumption is that these displays would be at a high-traffic and central location in the house (e.g. kitchen and living room), some users tend to hide them away from the start, put them in less accessible locations or turn them off after a while (Bartram, 2015; Froehlich et al., 2012; Sun, 2014). The layout of the house, visibility of the screen (e.g. issues like location, natural or artificial lights), interactive affordances and aesthetic compatibility pose some constraints as well (Froehlich et al., 2010; Makonin et al., 2013; Rodgers & Bartram, 2011). Another important limitation is that the users need to be interested in energy savings and pro-environmental behaviour in the first place to acquire such a display and regularly use it in their daily lives without losing interest, which is not always the case (Barreto et al., 2013; Pierce et al., 2008; Strengers, 2011).

Ambient Feedback

ZPartially related to IHDs, ambient eco-feedback designs are meant to communicate instantaneous information to users via their peripheral attention and blend in with their living environment. While IHDs require users to be close enough to read and investigate the visualizations or data (Makonin et al., 2013), ambient displays can be informative from a further viewing distance. Researchers suggest that ambient feedback can unobtrusively and unconsciously persuade users, and influence positive behaviour (Jafarinaimi et al., 2005; Kim et al., 2010; Rogers et al., 2010). They are assumed to not require much attention and effort, deliver a more general message on an unconscious level rather than raw data and avoid an overload of complex information. To quote Quintal et al. (2016), “sometimes less information is more”. Simple and glanceable visualizations are usually highly preferred due to their convenience (Froehlich et al., 2012). Instead of answering questions regarding the actual amount of energy consumption, ambient feedback designs aim to answer more broad and simplified questions such as “Am I consuming too much energy / meeting my goals?” or “Does this appliance use any power right now?” without getting into many details. Bartram et al. (2011) mention that “participants really wanted to know “how they were doing” in the context of their particular goals (financial, energy use) and how this changed over time and events.” Therefore, ambient feedback is not intended to accurately and detailly inform the users of the data, but usually to create an awareness of it, hence it is not an effective way to learn the actual amounts or make comparisons based on these designs compared to digital data visualizations.

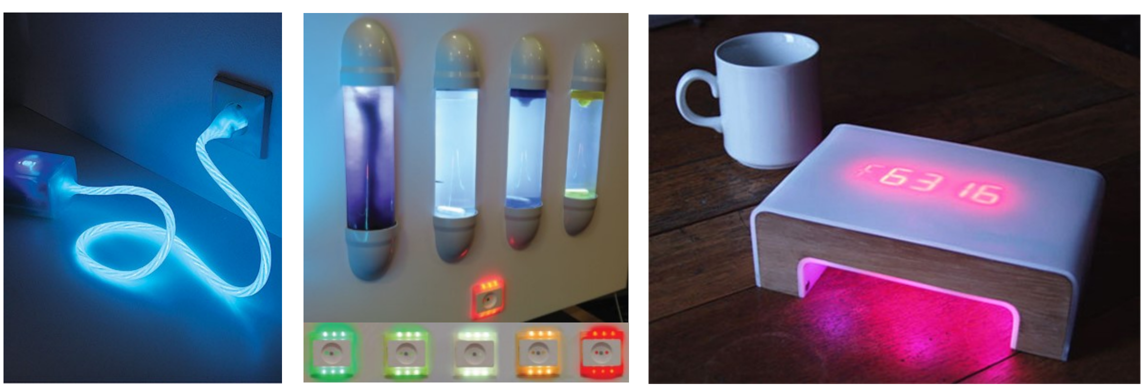


Figure 2-9. Ambient energy displays (left to right): (a) Power-Aware Cord (b) Watt-I-See ambient energy source visualization (top) and power draw visualization (bottom) (c) Wattson Energy Monitor

These kinds of designs could arguably be more interesting for people who are not quite interested in investigating their data in the house, comparisons or energy-saving tips (especially children or household members that don't usually check energy-related data (Neustaedter et al., 2013; Strengers, 2011)), simply because ambient feedback presents the message without any input or effort from the users. By creating awareness and sparking curiosity, they can encourage users to analyze and understand their energy consumption (Quintal et al., 2016). Rodgers and Bartram (2010) observed that Ambient Canvas has incited enthusiasm and curiosity from a variety of visitors that viewed the design.

Visual examples of ambient eco-feedback that display the *current power draw* include ecoMeter 'traffic light' feature, PowerPlayer green and red light signals, Power-Aware Cord and Watt-I-See (Quintal et al., 2016) (Figure 2-10a, b), along with audible feedback designs that alert the users of excessive energy use (Darby, 2010). Although alerting strategies have been shown to be effective (Black et al., 2009), in some of the studies, participants found the alerts and red lights anxiety-inducing and alarming (Darby, 2010). As one participant pointed out while using Watt-I-See, there are some occasions when users might not be able to simply stop using an appliance just to change the state of the red light, therefore they may feel pressure and anxiety as a result (Quintal et al., 2016).

Ambient designs have a high potential to influence in-the-moment decisions. The immediate and intuitive feedback provided by the PoC designs after using an appliance can make it easier to understand how much each appliance consumes. Supporting this assumption, Rodgers and Bartram (2011) observed that users tend to make quick cause-and-effect checks while they are using appliances to see how consumption is visualized.

There are also ambient displays that visualize the overall resource consumption in the house, even though they are less explored. Examples include Wattson (Figure 2-10c), InfoCanvas, Aquatic Ecosystem (Froehlich et al., 2012), Ambient EnergyOrb and Ambient Canvas (Figure 2-11). While the Ambient Canvas visualizes consumption through the kitchen backsplash (Rodgers & Bartram, 2010), Aquatic Ecosystem demonstrates the water savings through fish and plants in an aquatic environment (Froehlich et al., 2012). These kinds of visualizations aim to be the constant reminders of the household's overall resource use or savings by staying in the background of users' lives. This aspect allows users to be aware of their current process and decide accordingly, instead of receiving a bill after a month and trying to understand at what point they could have saved energy or water.

Figure 2-10. Ambient visualizations (left to right): (a) Ambient EnergyOrb (b) Ambient Canvas kitchen backsplash display.

On the other hand, an ambient visualization design by Rodgers and Bartram (2011) demonstrated that a display screen can cause a distraction and annoyance in a living environment and close proximity to other user activities (e.g. next to the TV when watching a movie). Likewise, the Ambient Canvas brought attention to the issue that the illumination need in the kitchen and countertop is an important consideration. Therefore, studies suggest that ambient designs should avoid being disruptive and obtrusive, support users' other activities in the house and fit well into the home environment while also being accessible and effectively creating awareness (Bartram, 2015; Rodgers & Bartram, 2011).

Aesthetic Visualization and Art

In his study, Kosara (2007) establishes a categorization of visualizations based on their artistic approach. This categorization consists of a spectrum from the very analysis and technical-oriented pragmatic visualizations, to artistic visualizations that are more suited for expression and communication of a concern. He argues that while pragmatic visualizations aim to provide efficiency, thorough and immediate understanding, and data accuracy; artistic ones are meant to present an enigma, have a sublime quality, and evoke curiosity and interest in viewers. Visualizations that spark an emotional response are implied to have a more memorable impact on the viewers

(Bateman et al., 2010). To quote Petersen et. al. (2004), “aesthetics has the ability to surprise and provoke and to move the subject to a new insight of the world”.

Since one of the main goals of eco-feedback is to attract the users’ attention to the visualizations, the aesthetic appeal of the displays plays a significant role. Similarly, the ability of IHDs to fit in with the overall aesthetic décor of the house impacts the decision of the users to acquire and display them in their house. Artistic visualizations have the possibility to be enjoyed and displayed proudly, instead of being tucked away out of view. Pierce et al. (2008) also mention that they can serve as a representation of a person’s environmental values and lifestyle. According to Skog et al. (2003), artistic visualizations are “lived with rather than used”, thus their aesthetic values are paramount.

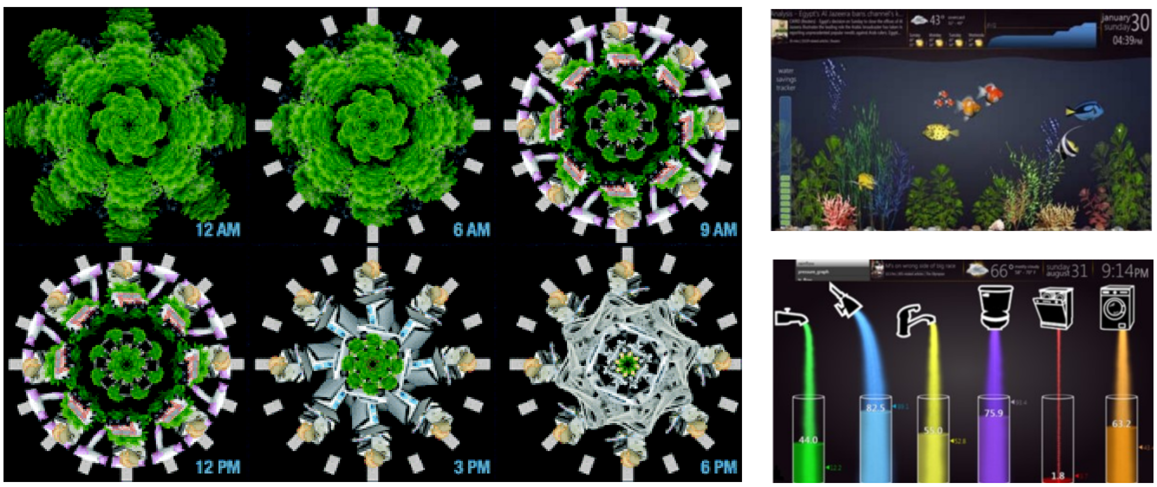


Figure 2-11. Artistic visualizations (left to right, top to bottom): (a) 7000 Oaks and Counting (Holmes, 2007) (b) Aquatic Ecosystem (Froehlich et al., 2012) (c) Rainflow (Froehlich et al., 2012)

Froehlich et al. (2012) observed that users found the artistic and ambient visualization, which shows water savings using an aquatic ecosystem, playful and educational, especially for their children (Figure 2-12b). They noted the issue of guests being able to see their personal and private data, however, they also mentioned that the Aquatic Ecosystem view might be used to “brag to our friends when they come by”. This implies the fact that users would be encouraged to share their achievements through a visually appealing design, which could also initiate discussion and engagement about the subject. Rodgers and Bartram (2011) also found out that users felt encouraged to display the artistic visualizations on their fridge or as a picture frame, saw its potential to become a conversation piece and thought that other people would be drawn to it due to its “artsy uniqueness”.

Due to its subjectiveness, artistic visualizations can influence different levels of pleasure and enjoyment. Customization could be a very useful feature so that it can appeal to many different tastes and preferences. Participants in Rodgers and Bartram's (2011) study expressed their desire for customization so that the display could fit in with their house aesthetic or mood. One participant mentioned that they might get bored and would like the ability to change the visualizations. Froehlich et al. (2012) also highlight the different preferences each household member might have and how they would affect the aesthetic appeal of the display.

As mentioned before, several studies have shown that users are not quite acquainted with energy-related terminology such as kilowatts or pounds of carbon (see *Knowledge* section). Relatable and more graspable visual metaphors (e.g. trees, leaves) are argued to increase the comprehensibility of energy consumption data. The *7000 Oaks and Counting* project visualizes the estimated number of trees required to eliminate the CO_2 emissions produced by the energy consumption in the building (Holmes, 2007) (Figure 2-12a). Holmes not only aims to achieve this by visualizing consumption with trees, but also intends to evoke positive emotions and feelings with the aesthetic feature of the design, since "most individuals maintain positive feelings toward trees".

Similar to ambient feedback, artistic visualizations don't possess the qualities of pragmatic ones, and thus the ability to reach more detail about the energy consumption on demand also needs to be considered (Rodgers & Bartram, 2011). Liu et al. (2016) indicate that while their physical interactive display attracted people's attention, made them think, provide a playful visualization and initiated discussion among the groups of viewers, they also highlighted the importance of and need for an accurate and clearly comprehensible pragmatic visualization. Even though ambiguity sparked an interest and engagement, they observed that rich and flexible information visualization was harder to achieve with a tangible and artistic design. They concluded that neither visualization technique was superior to the other, each had its own advantages and disadvantages, and the two methods can work cooperatively. Supporting this statement, Skog et al. (2003) imply that designs should achieve a balance between artistic and functional aspects by being able to inform users clearly while also considering the aesthetic concerns.

Aesthetic visualizations also need to make sure the appealing aspect does not interfere with or result in the opposite effects of the goal. These visualizations aim to stimulate emotional reactions, but the way people perceive and react must be in line with the pro-environmental behaviours (Bartram et al., 2010). For instance, while the lights in Ambient Canvas aimed to show the energy consumption in the house and remind users to use less, because of its aesthetic appeal people preferred to see it fully lit, which was the opposite of its intention (Bartram, 2015; Rodgers & Bartram, 2010). Similarly, Froehlich et al. (2012) observed that the Rainflow display, which playfully visualized the consumption, might encourage children to use more water so that they can see the "pretty water flows" (Figure 2-12c).

2.2.5. Behaviour

Even though people are sufficiently informed, knowledgeable and motivated to conserve energy, in-the-moment decisions might not reflect their intention. Those decisions are mostly based on the perceived comfort and effort of performing actions, even if there are financial (dis)incentives (Darby, 2010). And since sustainable behaviours are often seen as a compromise in quality of life, people rarely conserve energy without any reason or motivation (Barreto et al., 2013; Froehlich et al., 2010; Pierce et al., 2008; Strengers, 2011). Bartram (2015) indicates that saving and managing energy is not an explicit practice, but it is highly dependent on daily activities and behaviours. Therefore, reducing the perceived effort factor of learning, understanding and acting on energy conservation behaviour is crucial for people to incorporate sustainable living into their lives (Chetty et al., 2008; Katzev & Johnson, 1987; Rodgers & Bartram, 2010).

Issues that prevent households to adopt eco-friendly behaviour often relate to lack of time, actionable insights, a desire to put extra effort and thought into daily activities and a reference point to compare (Barreto et al., 2013). Strengthening the link between energy consumption results and daily activities is important to develop sustainable behaviours. Eco-feedback designs targeting individual behaviours to highlight, rather than providing aggregate and general data, offer a better understanding of what habit changes need to be made (Pierce et al., 2008). Engaging users to reflect on their behaviours is assumed to be more effective than simply providing consumption data. Furthermore, convenient and glanceable information is suggested to negate the perceived cost of time and effort required to understand energy consumption (Bartram, 2015).

However, some activities and behaviours might not be altered even if the users are sufficiently informed and motivated. Household members might perceive certain actions as non-negotiable, therefore dismiss or disregard the information (Barreto et al., 2013; Strengers, 2011). Comfort and convenience play a significant role for users to decide what is essential and what behaviours can be changed. With some feedback designs, it is unclear what consumers should do to reduce excessive use. People can be convinced that they are already using the minimum amount, and this can eventually lead to consumers stopping to use the feedback displays altogether. That is why providing *actionable* information and advice is crucial.

Barreto et al. (2013) also discuss the social inaccessibility of feedback design as a reason for the lack of behaviour change and adoption of the eco-feedback systems. In some families and households, only a select number of members take charge of energy management in the house, therefore leaving other members clueless about their own energy consumption information (Neustaedter et al., 2013; Strengers, 2011). Designs that are able to reach, empower and include every member, therefore, have more potential to impact their energy behaviour.

Chapter 3. Research Motivation and Goals

3.1. Design Motivation

As a result of the background review discussed in *Chapter 2,* this project aims to improve on the weaknesses of eco-feedback designs while considering the previous designs' strengths and incorporating methods that haven't been explored in this field yet. The main goal of the design is to seamlessly and unintrusively introduce energy consumption feedback into people's everyday lives and routines in order to increase awareness and promote motivation to save energy. To achieve that, the design intends to make use of ambient eco-feedback and physical visualizations within objects that are already used in households.

Although it isn't still clear how an eco-feedback design can reach its full potential and be as effective as it is intended, there are some common agreements among the many research studies done on this topic. It is not possible to set a list of rules to follow or design a one-size-fits-all eco-feedback method, however, the findings of these research studies point to some key points of the visualization designs, which are estimated to have a contribution to the effectiveness of informing users and encouraging energy consumption. To guide the project decisions, some design implications and considerations are based on said strengths and weaknesses of the previous eco-feedback designs in the following section.

3.1.1. Design Implications

One of the most important requirements of eco-feedback designs is considered to be comprehensibility and accessibility by several research studies. A major issue of several designs is that they are not easy to understand and require a considerable amount of time, effort and interest to investigate. Studies suggest a few methods to achieve information clarity:

- Including different levels of **data and time granularity** to provide immediate feedback and illustrate vampire energy, activity patterns and individual appliance consumption,

- Additionally including more relatable and relevant **measurement units** to enhance understanding,

- Utilizing various forms of **visualizations** to display data,

- Designing **simple and clear interfaces** that users can navigate easily, while also being able to 'dive deeper' into the data,

- Creating designs that fit into people's daily lives better so that the information is **accessible** to all members,

- Designing **intuitive interactions** by making use of existing behaviour, knowledge and skills,

- Providing **at-a-glance awareness** with ambient visualizations while also creating **slow and consistent awareness** by allowing access to in-depth data,

- Allowing **comparisons** to make sense of the data and understand the state of one's energy consumption,

- Providing **actionable information** and prompts for users to know how to improve their energy-saving efforts.

Simply knowing and understanding energy consumption data is not enough to change consumption behaviours and increase energy savings. Many people have different motivations while using or saving energy, and designs should be able to consider different perspectives while also trying to increase motivation to conserve energy. Some design implications to increase motivation and interest include:

- Providing **comparisons** in different ways to fit varying needs, such as self-comparison, goal-comparison or social-comparison,

- Encouraging users to **commit** to a certain goal,

- Avoiding discouragements that instill feelings of guilt and shame, and using **neutral feedback or rewards** that encourage pro-environmental behaviour instead.

- Driving people to **reflect, discuss and emotionally engage** with the energy consumption data using an artistic and aesthetic approach,

- Informing users about the effect of their actions, in other words, **showing the result of their efforts**.

Another important design requirement, especially for designs that are aimed to be located in users' homes, is to consider customization and visual appeal. Though many eco-feedback designs prioritize function, aesthetic appeal and personal customizations can engage users more with the products and develop an emotional connection. It is important for users to enjoy the device for them to continue using it and be impacted by it. For this reason, researchers suggest designs to:

- Be able to **fit into the users' homes**, both aesthetically and functionally,

- Allow user **customization** for enhancing both the interaction and engagement,

- Considering the social interactions, such as arriving guests or relationships between household members, and **ensuring privacy** to avoid household conflict.

The energy feedback design in this thesis study utilizes these implications as a guideline. This project explores how knowledge from past studies can be applied together to achieve a design that effectively encourages energy-saving behaviour.

3.1.2. Additional Methods

In addition to the existing eco-feedback designs, this project is also influenced by other methods of visualizing data and user interaction. These novel methods are aimed to be incorporated into the eco-feedback design as a different way to improve the user experience and interaction regarding energy consumption. These methods are identified in the literature as Tangible Visualization and Slow Technology.

Physical Visualization

With the advancements in technology, many aspects of our lives start to shift into the digital and mobile environment, decreasing their visibility and material presence in our lives. The invisibility of energy consumption is already an issue for awareness, knowledge and understanding, thus bringing this concept into our material environment has the potential to fill this gap. Digital visualizations and data are insufficiently comprehensible at a glance for many people, especially children. Similar to artistic and ambient visualizations, physical visualizations have the potential to be more engaging and educational. As mentioned before, the high cost of time and effort required to understand the energy consumption data deters people from analyzing their eco-feedback (Bartram, 2015). Utilizing the objects and tools that people use in their daily lives mitigates the learning and understanding process, and it is possible to increase the fast and easy comprehensibility of visualizations (Bartram et al., 2011; D. Huang et al., 2016).

Digital features usually require devices with displays to be turned on or illuminated in order to be useful. Unlike digital visualizations, physical objects do not come into existence, nor do they disappear after use, but they stay in place without the need for a screen. Due to their physical existence in people's living environment and experiences, tangible visualizations can be more accessible and intuitive (Moere & Patel, 2009; Zhao & Moere, 2008). Studies show that material representations and visualizations can be seen in prehistoric findings, even before the invention of writing

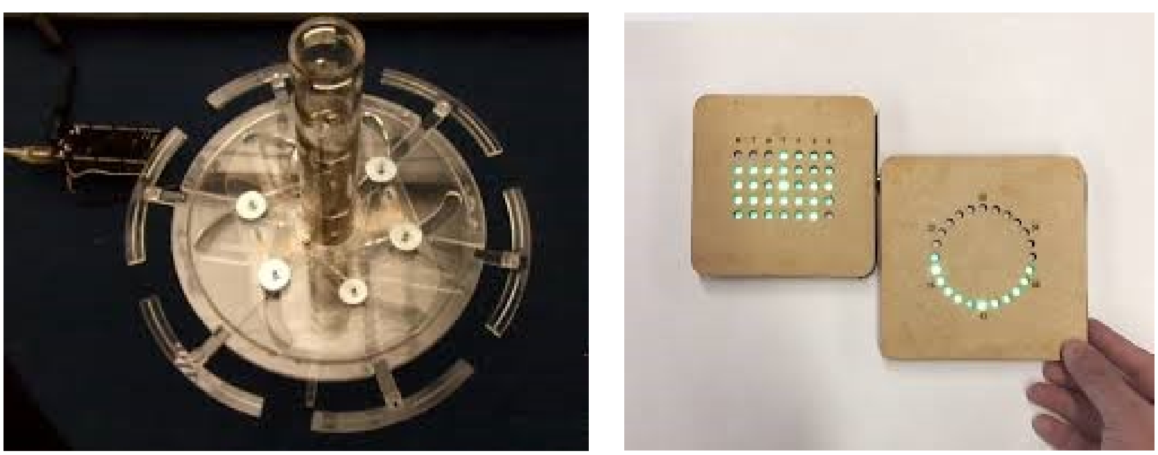


Figure 3-1. Tangible visualization and interaction examples (left to right): (a) Weather Lamp prototype that physically visualizes weather data (A. Wu, 2010) (b) Time Turner prototype that visualizes family moments on calendar with coasters (Singhal et al., 2017)

(Schmandt-Besserat, 1996). Yvonne Jansen (2014) argues that due to the changes in lifestyle and technological developments, “the physical origins of information visualization have been mostly forgotten in the field”. Recent studies in human-computer interaction (HCI) explore tangible visualizations (e.g. Jansen, 2014; Moere & Patel, 2009; Ullmer et al., 2001; A. Wu, 2010; Zhao & Moere, 2008) and interactions (e.g. Antle et al., 2009; Singhal et al., 2017; Ullmer & Ishii, 2000) through the combination of digital information with physical representations (Figure 3-1). Tangible visualizations are argued to be more expressive, persuasive and effective than digital or 2D visualizations. The physical affordances of the embodied data can introduce different contexts or emotions to the presented information (Moere & Patel, 2009).

As the concepts lose their materiality, they also become easily acquirable and disposable. Odom et al. (2009) highlight the influence of function, symbolism and material qualities on attachment to digital products. Emotional attachment increases the engagement and the possibility of users maintaining and caring for the objects (Russo, 2010). Digital applications and websites do not necessarily engage users this way, nor are they hard to dispose of or turn off.

Odom et al.’s (2014) exploration of the emotional value of physical photographs as compared to digital ones shows that users interact with tangible objects in a much different, more emotional and meaningful ways (e.g. users keeping photos under their pillows or attaching them to their refrigerators). This implies the potential influence tangible interaction might have on creating a bond between the users and objects, enhancing the connection and interaction.

There are several physical data visualization examples and tangible user interactions but very few applications on product designs. This study intends to explore the outcomes of involving physical data visualizations in products that are designed for household use.

Slow Technology

While many research studies don’t associate slow technology as a motivating factor for encouraging energy conservation, this project aims to explore the possible emotional response and reflection opportunities between users and products that slow technology can bring to the table.

The philosophy of slow technology is based on creating products that slow down the interaction, consumption and disposal process of objects, making them a part of people's lives for longer periods of time (W. Odom, Banks, et al., 2012). Many current designs are aimed to increase the effectiveness of products, reducing time and effort put into the process of use, and providing instant gratification for the users. This leads users to adopt faster lifestyles, stress and work overload (Grosse-Hering et al., 2013). As users' interaction with objects starts to get shorter and less meaningful, their importance and emotional value decrease. Slow technology aims to encourage people to pause, live in the moment, take a step back to contemplate the interaction and reflect on their actions (Grosse-Hering et al., 2013; Hallnäs & Redström, 2001; W. Odom, Banks, et al., 2012).

Slow technology has been shown to induce a sense of anticipation, curiosity and emotional connection (W. T. Odom et al., 2014). It is argued that when people bond with an object, they tend to protect and keep it as a part of their lives, and try to repair or salvage it when it breaks (Russo, 2010). Grosse-Hering et al. (2013) suggest that this bond can encourage a positive change in users' behaviour. They summarize the factors affecting the product attachment discussed in several research studies as positive and negative memories, personal change, self-expression, group affiliation and social interaction, regular involvement and well functioning, and therefore make the assumption that the principles of slow design can indeed create an attachment by influencing the duration and change of interaction (memories, personal change), involvement and reflection (self-expression, involvement, well functioning).

As shown in slow design studies, even though lack of immediate control over how the product works can cause some frustration and impatience at first, it has been observed that after a while of getting used to the slow technology, users start to accept and appreciate the anticipation, even express that it creates a calm feeling, especially if that product is not essential to their everyday lives (W. T. Odom et al., 2014). While the Photobox in their study works in the background of the users' lives in a non-intrusive way, Grosse-Hering et al. (2013) have shown that having a slow design in a regularly used product such as a coffee maker could become a burden for people's lives under time pressure. Therefore, it is important to consider if slowing down interaction is valuable, meaningful and positive. Both studies have shown that slow design could create a 'special' experience when there isn't an immediate need for the product. This design choice could be highly effective especially if the product is intended to subtly exist in the background of users' lives.

3.2. Research Design

3.2.1. Research Goals

This research uses design as a means to further understand the design implications for products that aim to bridge the gap between the users and their energy consumption at home. The goal is to make a knowledge contribution to future product designs that both inform the users effectively and motivate them to save energy.

The research process consists of background research, product design and user study to gain feedback for the design. The product design stage is informed by the background research and aims to explore new methods in this field. User feedback is also a crucial part of the design process. Potential users offer a consumer's perspective and can bring the strengths and weaknesses of a design to light. Discovering the flaws and weaknesses can guide the designers to improve the design to achieve their goal, or realize that another approach might be more effective. Therefore, a user study is necessary to explore and improve the design implications in the eco-feedback and sustainable HCI field. User feedback is not only beneficial for observing the natural responses from people that are unfamiliar with the design, but it also allows designers to hear opinions from an outside (especially the consumer's) perspective.

Within the user study, the semi-structured interviews and interaction simulations have the goal of exploring the user experience without strict structures so that natural interactions and responses can be observed. The study probes into how the product would exist in the users' home environment and how it would affect their daily life activities and interactions with the goal of finding out the shortcomings and improvement opportunities for the product design.

3.2.2. Research Questions

How would a product that visualizes residential energy consumption exist in people's home environment?

This question specifically inquires how the users would introduce this kind of product into their home environment, meaning where they would place it, and how they would configure the visualizations and customize the settings. The placement provides a clue about how they choose to integrate energy use into their daily lives and how the product can be tied to their daily routines. For example, what does it mean if they choose to keep the product in a secluded and private place in their house? Would they choose a common area where other household members can also access this information? How would the product's utility affect their choice; would they treat it as just an eco-feedback device or would they also consider its primary functions?

The configurations, on the other hand, give us information about what users think the most important information is for them and how they wish to seek it. It can also highlight what features they find useful or unnecessary. From their choices of the setting customizations, we can also learn how they would prefer to interact with the product. Do they prefer a constant ambient awareness of their energy use or do they want to seek that information on a set routine? How much detail do they seek and when?

How would this product affect users' perception of energy consumption?

This project also aims to explore how this product can affect the users' energy consumption awareness. By altering the way this information is presented and accessed, it seeks to create an ambient awareness and easier access. Therefore, the objective is to investigate how well users can notice the differences in the visualizations and how effective these visualizations are for low effort and intuitive comprehension. Specifically, the goal is to explore how the physical and ambient visualizations might affect energy awareness and the motivation to save energy.

What kinds of consequences need to be considered when introducing energy feedback into people's daily lives?

This research is also interested in seeing what kinds of unexpected benefits or consequences this product can lead to by bringing energy use information into users' home environment. This includes not only how it would affect users' individual activities and routines but also the interpersonal dynamics of the household members and the possible social interactions with others. It also aims to see if the expected or hypothesized outcomes can be possible or in what different ways they can be achieved.

What kind of design insights and improvement opportunities can be gained from this project?

Lastly, this research aims to discover the strengths and weaknesses of this product, seek the ways in which it could be improved and highlight the important aspects that should be kept in mind for designing a similar product that visualizes energy consumption at home through everyday objects.

3.2.3. Approach

To answer these research questions, the process started with designing a product that utilizes an everyday object that is used in the house to visualize energy consumption. The design process started with brainstorming about what objects could be used, how the visualization aspect would be added a) without interfering with the primary function of the object and b) by effectively communicating the information to the users. The idea generation involved sketching and 3D modelling methods to explore the possibilities.

Following the idea generation, prototyping with various materials and methods was used as a way to further the design. The physical prototyping involved cardboard

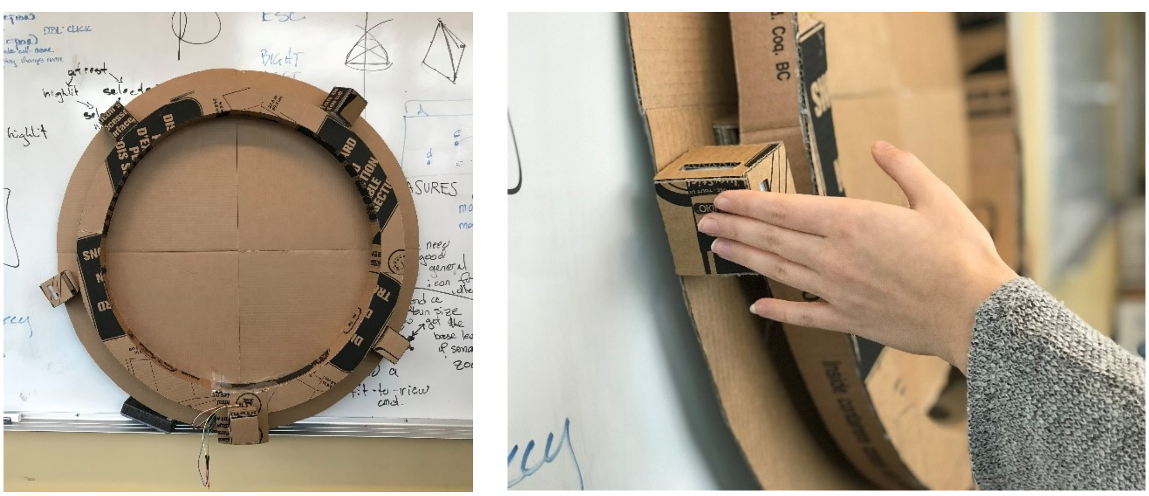


Figure 3-2. Initial stages of prototyping and idea generation involved tangible units and interactive design to access energy consumption data and control devices.

(Figure 3-2), styrofoam and wood materials as well as Arduino kits. Whereas for the software part of the prototype Processing and Unity were used.

Lastly, the user interaction simulation and interview were used as an approach to test the design and get user feedback. This part was able to provide some answers to the research questions that this project addresses.

3.3. Limitations

The ideal testing environment for this project would be to set up a real smart home system with the mirror and have participants live in this environment for a long period of time to test the theory that this design can provide users ambient awareness and knowledge about energy-consuming devices in their house, feedback of their energy-related activities and motivation to save energy. Due to the lack of resources to create such an environment, time constraints, and COVID-19 limitations that prevented human interactions in real life, this ideal environment could not be achieved.

Considering these limitations and the benefits of having user feedback in earlier stages of the design process, this study provides remote user feedback rather than real-life testing. As a result of doing the user study through video conferencing, the participants' view of the physical prototype was limited to a view through a webcam and their interactions with the application were limited by the remote control that Zoom provides.

Chapter 4. Energy Mirror Design

4.1. Design Considerations and Decisions

The first step of the design process was to determine how the product would be integrated into people's living environments and daily activities. The key consideration is that the visualization should exist in the background: an ambient visualization that is unintrusive to their daily activities. If the functionality of a product is obstructed by the visualization or vice versa, the design can cause annoyance and this can lead to users getting rid of or turning off the visualization aspect of the product. At the same time, it needs to be noticeable enough that the users wouldn't ignore it. Since the feedback is designed to be visual, objects that users might look at or exist in a place that all the house members spend time in are assumed to be better candidates for this idea.

Ambient Canvas, an earlier design by Bartram et al. (2011) made use of a kitchen backsplash which indeed was a place where an energy visualization could be integrated into the background and makes use of a high-traffic location of the house. However, the practical functionality of lights in the kitchen environment and the aesthetic look of the fully lit strings contradicted the goal of the energy visualization. Their studies demonstrated that the users preferred the kitchen backsplash to be fully lit, which is the opposite intent of the visualization.

Figure 4-1. An early design concept for the energy mirror in which the frame disintegrates into the mirror to grab users' attention.

During the brainstorming process, different household products were considered for this purpose and evaluated for the balance between these two opposing factors, such as coffee tables, clocks, etc. However, for some of the objects either the functionality of the product obstructs the potential of data visualizations or the visualizations hinder or disrupt the functionality. The assumption of this research project is that a mirror is one of the products which achieve that balance. It is something many people intentionally look at during the day, while leaving the house or unintentionally while simply passing by. Its frame offers the possibility of visualizing energy use information without interfering with the function of the mirror. It can also be accessible to all the household members depending on where the users decide to place it. Ultimately, it is an object that can reflect both the users' physical appearance and their energy consumption habits at the same time.

4.2. Product Design

The design makes use of both the mirror frame and the mirror itself for energy visualizations. On the wooden mirror frame, the energy consumption in the house is displayed with a physical visualization. The intention behind this decision is to bring the abstract concept of energy into users' lives with a physical embodiment to create

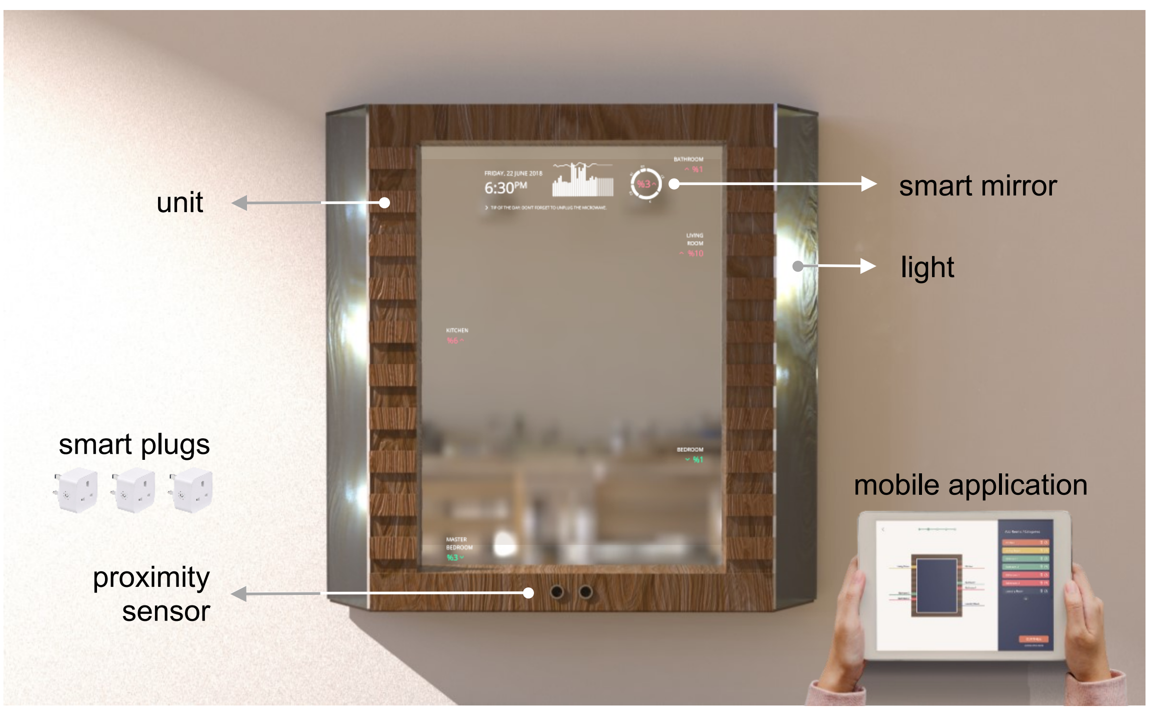


Figure 4-2. Energy mirror concept design.

awareness of its existence. Having the energy visualization constantly on display without a digital screen is hypothesized to increase accessibility and awareness for every household member.

The product design also shows the current power draw of the devices in the house. Many people think about turning off the lights to save energy even though it is one of the least energy-consuming products in the house (Strengers, 2011). Due to its visibility, it is natural that people associate electricity with lights. Based on this assumption, the current power draw in the house is visualized by lights around the frame.

The ability to dive deeper into the data is also a part of the design considerations. While the mirror frame provides at-a-glance quick information, the users need to be able to investigate their energy data further for a better understanding and future decision making. For this purpose, the mirror is connected to a mobile user interface that is similar to the commercially available mobile applications and websites.

Just between the surface level visualization and the information overload of the interface, the smart mirror provides a customizable dashboard for users to see relevant and summarized information, which only appears when the users are in close proximity. Additionally, the energy-saving achievements of the users are displayed with ambient designs to create interest and encouragement.

The energy data in the house is gathered by meters that collect energy consumption and power draw data from each device, appliance or plug so that the visualizations show accurate and detailed information. Being able to access the individual data for devices provides knowledge of how much energy they consume, and how often household members use the devices and therefore helps users to make informed decisions about how to save energy in the future.

4.2.1. Energy Consumption

The energy consumption in the house, more specifically the *excessive* energy consumption, is designed to be visualized by the pieces of the mirror frame. The initial idea for this concept was to create an effect of the frame disintegrating or creeping into the mirror in a way to attract the viewers' attention (Figure 4-1). The pieces of the mirror frame entering the users' field of vision are a metaphor for the product's purpose of incorporating energy use considerations into their daily thoughts and decisions. With this approach, the aim is to provoke the urge to *fix* the frame by returning the pieces to their original position and retaining the unity and order of the frame. In this case, the users can fix the frame by reaching their energy-saving goals.

The design of the frame and its pieces were explored in many ways, but for the purpose of gaining design feedback for this research study, a simple and practical approach is chosen for the prototype (Figure 4-3).

Figure 4-3. Units sliding from the frame into the mirror to indicate that there has been excessive energy consumption in the room/category that the unit represents.

The pieces on the frame, which are called *units*, represent different categories of energy consumption in the house. This categorization is up to the users and can be rooms in the house, types of devices or whichever category makes more sense for the users. This customizability is aimed to help the comprehensibility of the data. The users can assign these categories to the units of their choosing while setting up their mirrors. For example, based on where the mirror is located, the direction of the rooms in relation to the mirror can determine which room can be assigned to which unit by creating a mental map of the house. The set-up is done through the mobile application, the design of which will be explained in detail in the following sections.

After a week of gathering energy use data, the users will then set a goal for how much energy they want to consume or save the next week. The default setting compares the current week's progress to the last week's daily average. The users can decide to either set a goal for the whole house (e.g. using %5 less energy than last week) or set individual goals for the categories (e.g. saving %10 energy in the kitchen and %5 in the living room). The units reset every week and a new goal is set. The decision for the weekly reset derives from the effect that users' actions can make on the units. A daily reset is a short time to reflect on the daily energy-consuming activities, while a monthly reset would not give enough feedback for the near past events and actions, and it also means that excessive use would take a very long time to fix.

To explain what makes the units move and how excessive use is calculated, Figure 4-4a demonstrates a cumulative graph of an example weekly energy consumption of a household. This first week's data is used as a baseline to compare future energy consumption. The total amount of consumption at the end of this week is first multiplied by the next week's goal (for this example it is %95 of the last week), then divided by 7 to get the daily average goal. Figure 4-4b shows what the ideal cumulative graph for the next week should look like, with the daily average amount of consumption adding up every day. The actual cumulative consumption of that week is compared to this trendline, and whenever it is crossed, it means that excessive energy consumption has happened for that week so far (Figure 4-4b). When there is excessive energy consumption, the units move into the frame to alert the users of this situation. Then, the users can make informed decisions from that point onwards to reduce their consumption and reach their goals.

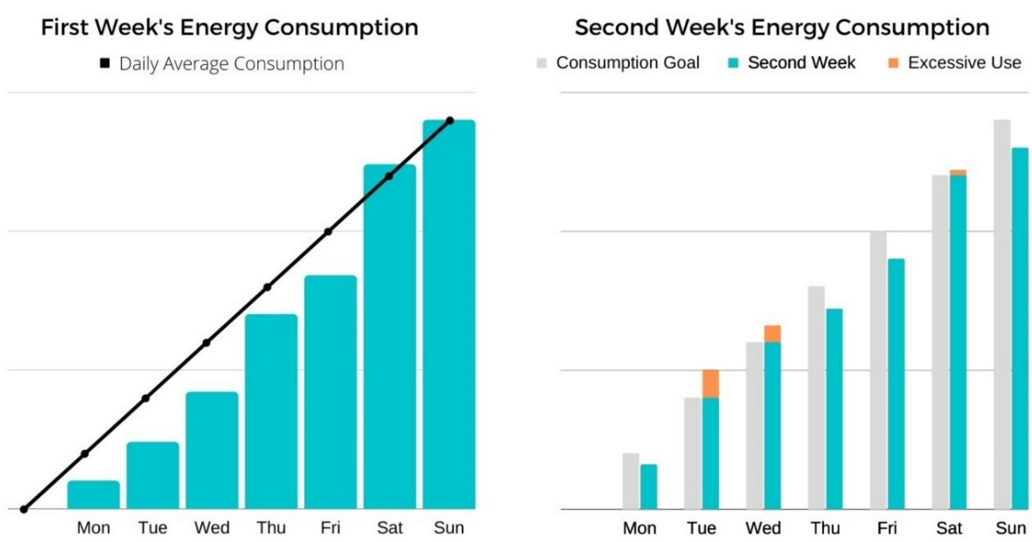


Figure 4-4. Example of how excessive consumption is calculated for the units (left to right): (a) First week's energy consumption and the daily average (b) Second week's consumption compared to the first week with excessive use highlighted.

Slowing down the process of returning the units back to their original position is intended to increase the awareness of household members' excessive usage by constantly reminding them of the current situation whenever they pass by the mirror and take a peek at it. The reward is expected to be perceived as more well-earned rather than the instant gratification of immediate awarding since they will be working towards the goal for an extended amount of time. Furthermore, the effect being a physical change is a much more tangible result rather than a number on a screen can be more effective in the users' perception. However, this aspect may also cause the household members to feel annoyed and frustrated that they can't simply fix the frame whenever they please.

On the other hand, since the units are not an active part of people's everyday routines, meaning that they do not particularly *need* the frame to get into its original shape to continue with their daily lives, the expectation is that it would not cause a disturbance more than it would if they actively used it - similar to the objects or appliances like coffee maker, TV, etc. (W. T. Odom et al., 2014).

Another goal of this approach is to create a connection with the users by engaging them in the process. Rather than following an abstract and intangible goal, this design aims to turn this goal into tangible results that all family members can follow and be aware of constantly. Instead of logging in to a website or an application, the mirror frame provides continuous feedback in a high-traffic location in the house. It creates a collaboration throughout the household to reach a certain goal, which is visible to every member of the house. According to Strengers (2011), not all the members of the household are aware of the energy consumption (especially children and teenagers); analyze and manage the consumption (generally the person who pays the bills); dominate the energy consumption in the house (usually the person who does most of the chores or uses the most electricity in the house), or are interested in eco-feedback or sustainable consumption. However, being visible to all of the members of the house without the need to use a device and understand statistics, the mirror frame can easily inform and make the household members aware of their consumption. It can also engage users in a discussion about their energy consumption and social collaboration to 'fix' the frame with a combined effort. Social discussion and collaboration are argued to be effective methods for awareness and resource conservation (Geller, 2002; Rodgers & Bartram, 2011; Staats et al., 2004).

4.2.2. Current Power Draw

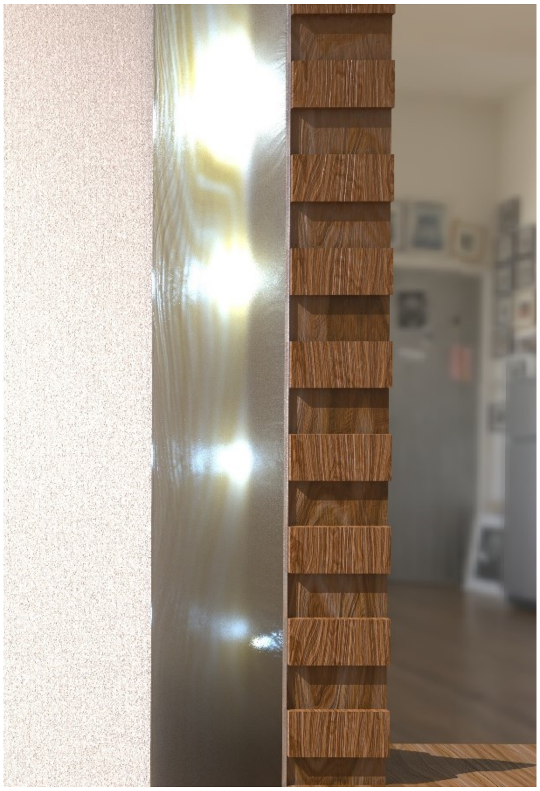


Figure 4-5. Lights around the frame represent the amount of power draw in the room/category they represent with their brightness.

The devices drawing power at the current moment are visualized with the lights surrounding the frame (Figure 4-5). This information can be useful for several reasons such as knowing what is currently on, understanding how much power devices draw and being aware of the vampire power in the house.

Knowing what is currently on could be useful for reminding users about the devices that are left accidentally on. This might especially be useful for people with anxiety and OCD as they are getting ready to leave the house. Although some devices always need to be working, such as the fridge or water heater, the users can exclude these from the visualizations in the settings so that they will only be shown devices they can have control over. Additionally, users can visually see the vampire power certain devices consume on "power-saving" mode and be reminded to unplug those to save energy.

Furthermore, this visualization can help people understand how much energy their devices or appliances consume. As mentioned in the background section, studies show that with a design in their house that visualizes this information, people make cause and effect checks to build knowledge about the energy consumption in their house (Rodgers & Bartram, 2011). In this prototype, the amount of power is represented by the brightness of the lights for each category (Figure 4-5). Although this does not provide a detailed number or comparison, it can create a surface-level understanding. The downside of such a visualization is that it can downplay the amount of energy that is consumed by the devices that work with low power but run for a long time (Strengers, 2011). Therefore, users can underestimate their overall effect on their total energy use.

4.2.3. Smart Mirror

How visualizations work on a smart mirror is very similar to digital visualizations on a screen. However, there is a limitation to the area that can be utilized so that the functionality of the mirror is not compromised. The aim of the smart mirror visualization in this project is to provide an overall look and a summary of the energy consumption in the users' houses. With the ability to customize the amount of information, type of visualizations and aesthetics of the design, users can be in control of what they want to see according to their own preferences. This contributes to the connection between the users and the product, as well as providing only useful and relevant information.

Figure 4-6. Smart mirror visualizations (left to right): (a) Customizable data visualizations (b) Ambient visualizations.

Shifting between the different views of the smart mirror is controlled by the proximity sensors located at the bottom of the frame. The default setting is that (1) the screen does not show anything if there isn't any person near, (2) if a person passes by or looks at the mirror at a certain distance the ambient visualization shows up, and (3) if the users want to see the data visualizations they can point their hand close to the proximity sensor to switch the mode. To switch between these modes, users can again point their hands to the sensor. The distances and modes can be customizable to suit the users' needs and preferences.

Data Visualization Display

The data visualization display works similarly to an energy dashboard and consists of widgets. These can either be different charts and graphs of daily/weekly/monthly consumption of the categories/house, personalized tips and consumption summaries (Figure 4-7), or they can be personal widgets that allow personalization such as date and time, news, tasks, calendar, etc. (Figure 4-8). Setting up and customizing these visualizations are done through the mobile application. Users can choose what they want to see as well as where they want to put the widgets on the mirror. Having the option to include personal widgets can improve the connection between the smart mirror and the user so that they are encouraged to use and look at the smart mirror.

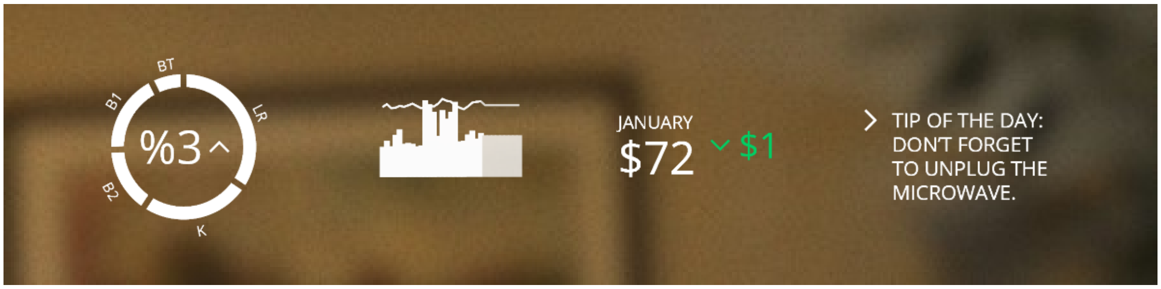


Figure 4-7. Energy consumption related widgets.

Along with the data visualization charts of the energy consumption in the house, the mirror screen also provides personalized advice based on the users' consumption habits. As previous studies have shown, information specifically tailored to the users is more useful for them to understand how to effectively save energy (Abrahamse et al., 2005). This kind of actionable information aims to act as a guide for the users rather than simply provide raw data for them to investigate and decide on their own.

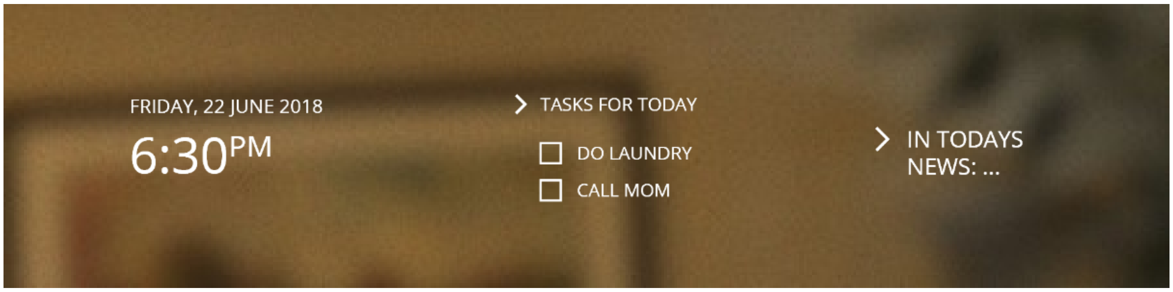


Figure 4-8. Personal and non-energy related visualizations.

In addition to the widgets, there are also information summaries for the categories that appear next to their respective units (Figure 4-9). This also makes it easier to remember which unit represents which category. Again, these summaries can be modified or deleted depending on preference. How the information is summarized is up to the users, meaning that they can choose to see how they are doing compared to their goal in terms of kWh, percentage or price amount.

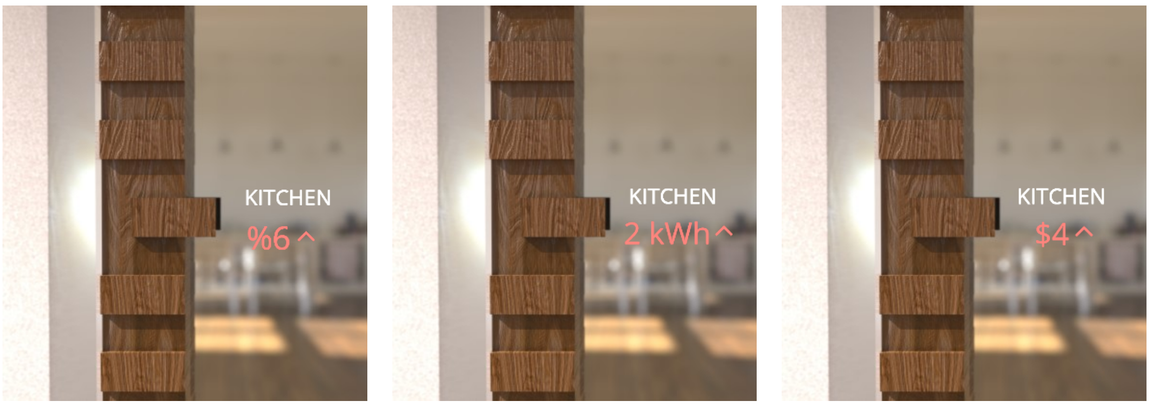


Figure 4-9. Information summaries for rooms/categories.

Ambient Display

Simply displaying data visualizations might not be encouraging or interesting enough for some users. For that reason, the ambient mirror display visualizes the users' achievements of reaching their energy-saving goals over time. With each week, a symbol representing the goal achievement appears on the mirror, the size of which symbolizes how much they surpassed the goal. The symbol changes according to the theme that the users choose.

The ambient display mode of the smart mirror was inspired by the selfie filters that many people use and love on social media platforms. Not only does this visualization give an idea of "how they are doing" in terms of energy saving, but it is rewarding their sustainable behaviour by creating a beautiful frame around their reflection, which is hypothesized to encourage users to continue to save energy. Of course, these filters also have an option of customization and are designed to be updated regularly (the same way as the filters on social media) to create more variety to choose from. While creating a pleasant view for the users, it also creates a real-life filter for those who like to share mirror selfies online.

Figure 4-10. Different customizable ambient visualization options.

With their aesthetic and playful designs, these visualizations are intended to be more accessible and interesting to all the members of the household. Additionally, it is aimed to incite conversation among the household members or with their guests, and spark curiosity about the subject. Users having guests over can display their accomplishments with pride, which might motivate both themselves to keep up with their goals and encourage the guests to consider their energy use and how they can also live more sustainably.

Another advantage of this abstract and obscure display is that it can provide privacy for the users. Having all their data displayed while the guests are invited over might not be appealing for many people. Having the ambient option prevents users to have to turn the detailed data visualizations on and off to protect their personal data.

4.2.4. Mobile Application

The mobile application is used for a few different purposes: setting up the mirror for the first time, viewing energy data in detail, and customizing and adjusting the settings.

In the initial setup, the users first connect the mirror to the application using a Bluetooth connection. Then, they can categorize the electrical devices and appliances in their house (e.g. divided by rooms, type, the amount of energy used, etc.) and assign these categories to the units in a way that is logical for them so that they can make sense of the visualizations in the future. Next, the users will add devices to the rooms by selecting the type of device and connecting them to their relative meters or smart devices. Finally, users will customize their smart mirror visualizations and settings.

After the setup, the application will display an energy dashboard that visualizes several aspects of energy use in the house. This dashboard is also customizable since the arrangement of the visualizations works in a similar way to the widgets in smartphones and tablets. So, users can move around, delete or add and change the size of these visualization widgets so that they are able to see the most relevant information for them and hide the ones that are irrelevant or uninteresting. If the users want to investigate the visualizations in detail, they can tap on the widgets to expand them.

Figure 4-11. Mobile application screens.

On the dashboard, users can set their goals for the next week. Their goals can either be set as a percentage of the last week's consumption, a price amount of the bill they need to pay, the average kWh they aim to consume or the total kW amount in the next week. As a reference, the application shows the previous week's amounts so that users can estimate what goal they want to set for themselves. They can either set a goal for the whole house, or they can set individual goals for the categories. For example, they can commit to using %10 less energy in the kitchen but around the same amount as last week in the bathrooms.

Some examples of the visualization widgets include bar graphs of weekly and monthly energy consumption in the house, a pie chart showing the contributions of categories with a percentage of the current total compared to the last week in the middle, daily personalized tips to save energy, and devices currently in use in the house. Within the weekly and monthly bar graphs, users can compare their consumption to the weather, similar houses in the neighbourhood and their past year's energy consumption - if that data exists. Their excessive use in the day is visualized with different colours on the bar graph to highlight the relevant information.

Additionally to the dashboard, the tabs on the side menu offer different views for alternative visualizations or even more in-depth data. The second tab from the top shows the general views of the categories, and by tapping the category blocks users can get access to information about each of the devices and how much their consumption contributes to the overall use in that category. The last tab on the side menu takes the users to the settings where they can adjust their customizations if they want or need to change them.

4.3. The Prototype

A prototype of the product design was built to demonstrate the functions of the mirror for user feedback. The physical form of the design was constricted by the readily available and quickly accessible materials, therefore the visual design of the product mostly reflects the function. For example, the measurements of the monitor and two-way glass mirror used for the smart mirror limited the size and shape of the mirror frame. However, with parts that are specifically designed and manufactured for this product, a future design of the concept can afford to be thinner, made in different shapes and materials to be more suitable for the house décor, since the aesthetic aspect is an important part of the project.

The components of the product consist of a plywood frame, a standard monitor with an HDMI connection, a two-way mirror, an Arduino hardware with servo motors, 3D printed pieces to connect the motors to the units to push and pull them into the mirror, a proximity sensor, LED light bulbs around the frame and a semi-transparent acrylic sheet to cover them (Figure 4-12). The two-way mirror is reflective on one side and transparent on the other, which makes it possible to show the reflection while also allowing light to pass through. The monitor is located behind it, which displays the digital visualizations that show through on the mirror, creating the smart mirror effect. The Arduino hardware

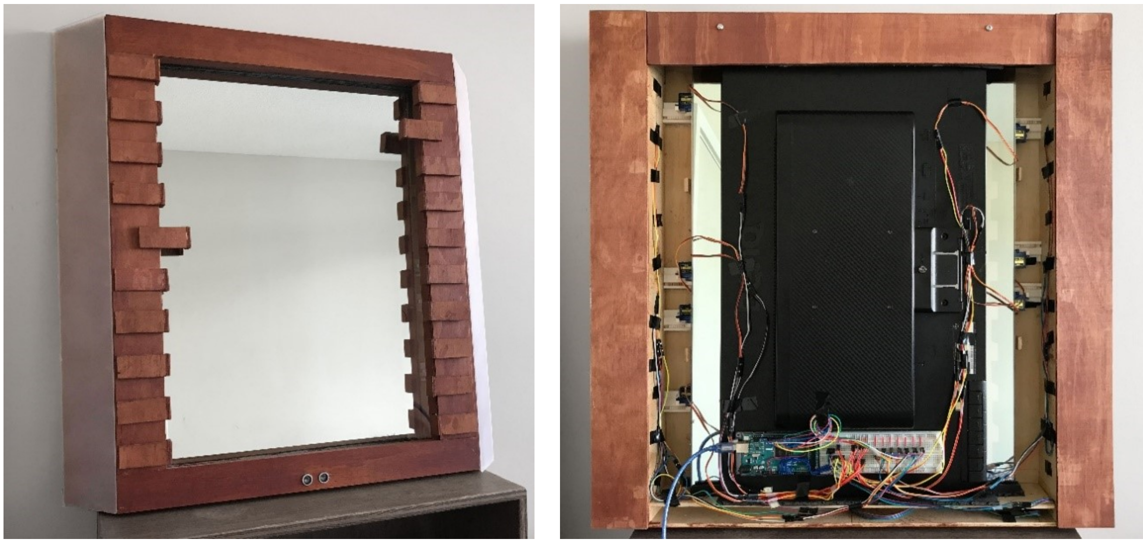


Figure 4-12. Front and back images of the mirror prototype.

is connected with USB to a computer, which acts as a communication platform between the Arduino software and the mobile application created in Unity.

Ideally, the energy consumption data that the dashboard in the application and the units are driven by should be connected to meters around the house that collect this information. Due to the lack of resources and a controlled environment to set up such a system, a fake energy data simulator was created. In this simulator, information about the house - such as rooms, devices and *watchfulness* of the user - is input and the program generates a fake history of energy consumption for a week. The watchfulness value determines how much the user tries to save energy by turning the appliances off or unplugging instead of putting them into standby mode or how often they turn on the devices. Then, the watchfulness value is changed based on the set goal and the energy use for the next week is generated. With this value, weekly energy consumption data is generated and visualized in the dashboard and the mirror screen.

Chapter 5. User Study

5.1. Procedure

The user study was conducted with 10 participants through video conferencing over Zoom. The participants were recruited through emails to graduate students of SFU School of Interactive Arts and Technology, invitation posts to Facebook groups and word of mouth. The participants consist of ages ranging from 23 to 65, with an equal amount of male to female ratio. Each study lasted for about 90 to 120 minutes.

The prototype of the product was used as a part of the user study. The participants were presented with the physical prototype through a webcam, while the prototype for the application was presented through screen sharing. The participants were given remote control through Zoom to interact with the application. With the same feature, they were also able to draw their house layouts.

The studies were video recorded using Zoom's record feature. 4 out of 10 interviews were conducted in Turkish, and the rest were done in English. The transcripts of the English interviews were created using Otter.ai, while the Turkish interviews were transcripted using Microsoft Azure speech to text services and translated manually. Then, the process was followed by the data analysis which included coding the data using MAXQDA and Microsoft Excel.

5.2. Study Structure

The user study consists of 4 sections: introductory and demographic questions, product introduction and tutorial, user interaction simulation with a semi-structured interview, and follow-up questions. The main part of the study is the user interaction simulation in which the participants will be asked to imagine themselves in different situations with the mirror so that insights from their behavioural choices, opinions and feelings can be collected. The insights and outcomes will be a useful reference for future design work regarding energy visualizations - especially physical and ambient ones.

5.2.1. Introductory Questions

The introductory questions aim to gather demographic and general energy consumption-related information from participants. Some of the answers in this section were used as a guide for the scenarios so that users could be presented with familiar and realistic situations to act in (e.g. their current living situation, people they are currently living with, etc.). Questions include information about their current living situation and energy consumption habits and knowledge. This information was also collected to see if there were any connections between their current energy habits and their answers to the questions about the product.

5.2.2. Product Introduction

In this section, the participants were objectively presented with the energy mirror design, its components and how it works, and a quick tutorial of the application. The presentation refrained from revealing the purpose of the features to avoid biased answers. The comments, questions and reactions of the participants to the different features were also noted during this section.

5.2.3. User Interaction Simulation

The user interaction simulation consists of different scenarios that participants imagine themselves in and react to. They were asked how they would feel and what they would do, as well as how they would interact with the product.

Setting up the mirror

The participants were asked to sketch out the layout of their current living situation. They were then asked where they would put/hang the mirror and some follow-up questions depending on their answers including the reasoning behind their decision.

User experience during daily activities in the house

The participants were presented with different scenarios in their house that are realistic for their current or imaginary situations. Their previous answers were taken into consideration and the scenarios were adjusted according to each participant (e.g. if they chose to put the mirror in the kitchen, the scenarios will involve activities taking place in the kitchen, such as “Imagine you are preparing dinner with your partner in the kitchen…”).

The scenarios are designed for them to react to or interact with the mirror’s different features and visualizations (such as lights around the mirror displaying the current power draw of the devices in the house, bars on the mirror frame visualizing excessive energy consumption, smart mirror displaying data and ambient visualizations) and possible social interactions with other house members or guests. The questions are also aimed at seeing how well they can notice the differences, what they think the changes mean and how they feel about the current situation of the visualizations.

Additionally, feature-specific or follow-up questions were included, some of them regarding the possible social interactions and privacy concerns.

Mirror Customizations

After going through the scenarios, the participants were asked to customize the settings of the energy mirror. These customizations include deciding what the bars around the frame will represent (e.g. categories of devices or rooms in the house), which bar will represent which category/room, what kind of visualizations they want to see on the smart mirror, etc. Depending on their decisions, there were follow-up questions to understand their reasonings, feelings and opinions.

5.2.4. Follow-up Questions

Lastly, the participants were asked some follow-up questions regarding their general opinions and feelings about the product design, such as what they think the weaknesses and strengths of the product are.

5.3. Data Collection

The following table outlines the research questions and data collection methods used for each of them.

Table 5-1. Research questions and data collection methods.

Research Questions	Data Collection Methods
How would the energy mirror exist in people's home environment?	✓ Layout Drawings ✓ Interviews ✓ Video Recordings and Observations
How would this product affect users' perception of energy consumption?	✓ Interviews
What kind of outcomes (consequences and benefits) can be seen from introducing energy feedback into people's daily lives?	✓ Interviews
What kind of design insights and improvement opportunities can be gained from this project?	✓ Interviews ✓ Video Recordings and Observations

5.3.2. Semi-Structured Interviews

The interview was designed to be semi-structured to allow for follow-up questions or modifications to adjust to each participant's case. It is also aimed to be flexible so that they can express their opinions and feelings fully without the restriction of a strict structure. The flexibility is beneficial for them to imagine themselves in more realistic scenarios and for allowing the interviewer to probe into topics that seem more promising for interesting outcomes.

5.3.3. Video Recordings and Observations

The majority of the observations take place during the section where participants configure their own mirrors and customize their settings. The observation of how they use the application and what information they seek provides beneficial information to improve the user experience. The video recordings of the user study also provide context for non-verbal cues for the interviews.

5.3.4. Layout Drawings

The layout drawings offer an additional context to where they would place the mirror as they provide a spatial understanding of the participants' living environment and how the mirror exists in relation to their living spaces, activities or furniture. As there would be major differences between where the mirror is placed in a room, a verbal answer would be insufficient to understand how the participants would integrate this product into their home environment. For example, the answer can be "living room", but it could be in a discreet corner or it could also be in a high traffic location in the living room.

5.4. Data Analysis

The data for this study were analyzed with consideration of the research questions that this thesis aims to answer. The analysis is based on a thematic approach based on these questions but also seeks emergent and unexpected results.

Table 5-2. Data analysis structure.

Topics	Categories	Sub-categories
Pre-study information	Personal information	Demographic information
		Current living situation
		Personality, habits and experiences
	Energy consumption	Awareness
		Motivation
		Behaviour
Energy mirror	Use in the home environment	Placement of the mirror
		Personal configuration
	Impact on daily life	Activities
		Emotions/Feelings
		Social interactions
	Energy consumption	Awareness
		Motivation
		Behaviour
Design feedback	Positive	
	Negative	
	Improvements	

The data analysis process starts with a thorough read-through of the data. Then, the data was coded into topics and categories. Within those categories, the data revealed emergent themes and patterns as well as exceptional cases. Table 5-2 outlines the categorizations of the data.

5.4.1. Pre-Study Information

The pre-study information was collected as a reference point for the following sections of the study. The data from the main bulk of the study was compared with this information to identify any correlations between the participants' past and current habits and their answers to the questions about the project. This information includes their current interests and habits regarding energy consumption, how their personality and experience affect their consumption and what motivates them to save energy (if they do).

5.4.2. Energy Mirror

This section consists of the main outcomes of the study regarding the product. Its subcategorization reflects the previously mentioned research questions of this project.

The first area of interest is how the participants would use the mirror in their home environment. This includes their choice of placement and their personal configurations of its features. The configurations consist of how they categorized their devices and assigned them to the units, how they customized the mirror screen and what settings they preferred.

The second topic investigates how the mirror could affect their daily lives. This includes their individual experience, meaning the emotions, feelings and activities affected by the product, and also their social interactions with both people they are living with and people outside their household.

The last topic deals with any discussion related to participants' perception of energy consumption including their awareness, motivation and behaviour. It contains conversations about how the product communicates the energy use information and how it could further improve their awareness and motivation.

5.4.3. Design Feedback

This category contains participants' opinions, feedback and suggestions for the project. Their opinions are separated into positive and negative according to how they felt about certain features. It also contains their improvements suggestions or comments that give insight about possible improvement opportunities.

5.5. Results

Subsequent to the data analysis, the results follow a similar structure to the categorizations of the topics mentioned above, mainly focusing on the *Energy Mirror* and *Design Feedback* categories in the data.

5.5.1. Placement, Comprehension and Utility

Mirror Placement

Participants' decision of where to place or hang the mirror gives an insight into how and where they would prefer to introduce energy use data in their home environment, what kinds of aspects affect their decisions and how the placement can affect their interactions with the mirror.

Participants chose to place the mirror near the entrance of their house (P2, P3, P4, P8), hallway or corridor (P1, P6, P7, P9) and the living room (P5, P10). A common pattern of reasoning for this placement turned out to be so that it can exist in a central, high traffic location in the house where all the household members can access it easily. However, there have been 2 exceptional cases. One in which the participant (P10) mentioned that a common area would be useful for other household members, which are her tenants, to see the energy information as well, but eventually preferred to keep the mirror in the living room where only she can access it and invite the others to look at it if they "need to be alerted". The second case is the participant (P3), who currently shares his house with a roommate that he is not close with, initially decided to place the mirror in a common area, but then changed his mind when he felt uncomfortable with the possibility of social outcomes during the later stages of the interview.

> "Are you assuming that I'm placing the mirror where I specified earlier? So near the kitchen? […] So in the first place, I would rather not to have it there. [Because] if you remember the last part of our conversation […] I would not want to have it shared." (P3)

Due to the nature of the product's design, the multifunctionality of the mirror and its energy feedback features affected their decisions. While only one participant out of ten prioritized the product's function as a mirror, others took its additional features into consideration while placing the mirror. When explaining their decisions, many participants mentioned that they would check themselves or their outfits in the mirror while also checking their consumption data. Participants who chose to put it near the entrance mentioned that they would check the mirror while leaving or entering the house, and how it could be useful for both their energy-related activities (checking if they accidentally left something on) and personal activities (checking the weather widget to decide on what to shoes or jacket wear).

Interestingly, participants did not prefer private spaces in their homes such as the bedroom or bathroom where a mirror could also exist. One participant (P3) specifically emphasized that he does not want data in his private space and that the numbers give him a sense of intrusion in his private life. Therefore, he would rather prefer to place the mirror "somewhere that belongs to the outside". Some participants mentioned that they would not place even a regular mirror in their bedrooms as well, citing personal preferences and cultural beliefs.

For some of the participants, existing notions based on previous experiences also affected their decisions. For example, one participant (P4) mentioned that she prefers to place the mirror in the entrance because that's where the electrical panel usually is. Another participant (P2) recalled a memory when he went to a smart home and the control unit was close to the entrance door and mentioned that that is why he chose the entrance.

Personal Configurations

Unsurprisingly, the way the participants assigned the rooms or categories to the units and how they decided to configure the mirror screen differed for each person according to their personalities, wants and needs.

The participants were informed that they could either categorize their devices and appliances into either rooms or categories, and all of the participants decided to categorize them into rooms. It is important to note that the examples shown to them during the product introduction had rooms, so that could have been a contributing factor to this decision. Only one participant (P3) chose to separately assign the lights (because he believed them to be one of the main elements that consume energy) and his laptop (because he was curious to know how much energy it consumes).

While some participants assigned the rooms to the units based on their location in the house, some preferred to categorize them around the frame based on the activities or devices within the rooms. For example, two participants separated the rooms that only use electricity from the rooms that use both electricity and water. Participants who assigned them according to their location either took the mirror as a reference point or considered the proximity between the rooms or their proximity to the entrance of the house.

When it comes to the mirror screen configurations, the results showed no significant pattern for what people want to see. Some people wanted to get immediate feedback from very simple visualizations, while some wanted to see the visualizations and trends over time. Some wanted to keep it simple and focused mostly on energy-related information with little to no personal widgets, while some preferred to add more personal widgets than energy-related visualizations and even asked if more options could be included. This demonstrates the importance of options and customization opportunities so that people are able to see the information that they need or want to see.

As expected, for the room visualizations, most of the participants (except for one) preferred to see consumption data in terms of dollar and/or percentage rather than kWh. The participant (P10) who preferred the kWh summary expressed that she is “an introverted thinker, analyzer” and “a fan of data”. Another common point is that the reason some people placed some of the visualizations or widgets at the top of the mirror screen is because they would attract more attention than the ones at the bottom, either to check what’s important for them or so that outsiders don’t see the personal data.

Some of the participants preferred not to use the ambient visualizations for their own configurations. While one of the participants (P6) thought it was unnecessary and skipped the preferences page, another participant (P3) expressed that he preferred not to use it because he wanted to keep the mirror screen very simple. Some participants also suggested alternative options for the ambient visualizations. One suggestion was to implement background images rather than shapes (P2). Another participant (P8) mentioned that he would prefer a closer metaphor for the environment, which is the reason he wants to save energy for. So he suggested that visuals like trees or desert could be added to give an idea about how the users are doing.

Comprehension and Awareness

During the interaction simulation, participants were shown the prototype in a state where some of the units were moved and some of the lights were showing different levels of brightness. Some interesting insights were found when participants were asked what they noticed different about the mirror and what they think it means.

When asked what they notice different about the mirror, 4 out of 10 participants did not notice the lights and 2 out of 10 participants did not notice the units. There might be several reasons that these features were not noticeable enough. One participant (P6) did not notice either the lights or the units and he mentioned later that it was because he was not able to see them through the camera. Since the interviews were done remotely through video conferencing, their view of the product is not as clear as it would be in person. Therefore, it might have affected this result. Another participant (P3) mentioned the fact that since the prototype was handmade, some parts looked crooked. So, it might have been another factor that made it harder for the participants to distinguish the altered units. Some participants suggested that the units could be thinner and longer so that it is easier to see the differences.

Some confusion was observed regarding what the units and lights mean. Even though the lights don’t necessarily show excessive power draw, some participants interpreted the lights as being an indicator that they are using a lot of electricity somewhere in the house. When asked what they would do when they saw the mirror in this situation, the majority of the participants’ impulse was to go and check if there was something left on or if there was something that could be turned off.

Another case of confusion was regarding the relationship between the lights and units. These two features represent different pieces of information related to the room or category that they are assigned. Even though they each mean something different about the energy use, one being the current draw and the other being the excessive energy use, some participants were confused about what exactly they meant and/or how they are connected to each other. Several participants asked again to clarify what they mean, which can be construed as an indicator that it isn't intuitive or easy to understand. One participant's comment while guessing the percentages of the units is an example of this confusion:

> "...based on the light, I want to say the [unit] on the left-hand side is... should be more but just looking at the wooden block, yes, they both look 30%." (P7)

When she was asked about what she thinks about the current situation of the units, she also took the lights into consideration:

> "So, if I am able to figure out which appliance is leading to that light being so big, then I'll see that, okay, can I turn it off? If I can, then I'll do that." (P7)

Another participant's comment on the intuitiveness of the physical visualizations could be considered as a probable reason why there was some confusion regarding these visualizations:

> "I think the level of details are pretty clear in the mirror and application because that's what we are pretty used to, like those data visualizations. But for the tangible part, I think the unit and the light feel a little bit awkward combined together because it's not very intuitive for us to sense the electricity consumption through this kind of form. […] I don't feel like the units and lights are helping much with it, although they are tangible and tangible is good to me, I just feel like they can be integrated better. And having more metaphor in it perhaps." (P1)

5.5.2. Outcomes of the Mirror's Presence at Home

Awareness

Due to the product's multifunctionality, many of the participants believe that the mirror might be useful to be aware if something is 'off' about their energy use. As intended with the design, participants presume that they would check their energy consumption while also checking themselves or their outfits.

There are different types of awareness that this product aims to achieve. One is to make users aware of the devices consuming energy in the current time, especially to bring attention to things that are left on or highlight high energy-consuming devices. The participants also took that aspect into consideration while deciding on where to place the mirror, so that they will have a chance to check if there's something left on before leaving the house or being aware of devices in the other rooms while spending time in the living room.

> "So I think, yeah, this wall would be perfect because... well, like, before you leave the house, right? So then you can see […] if you have left something on. […] We always have this stress, or at least I, you know, 'Oh did I leave the oven on or something?' So, you know, if you see, like, the light for the kitchen is super high or... or the tiny tab is moving too much towards the center, then you're like 'Whoa, maybe something's up'." (P8)

The second type of awareness that the product tries to create is to alert users about excessive consumption through the units. Based on the initial reactions of the participants and what they said they would do after seeing the units move, the awareness of the devices that are currently drawing power seems to be more prominent. Some of the participants' initial impulse was to go and check what could be consuming a lot of energy and turn them off if necessary, rather than trying to figure out what caused the problem from the visualizations of their past energy use. Although there have been participants who wanted to figure out what has happened through either the mirror screen or the application (noting that they would prefer which one is closer or convenient), the reactions were more immediate action based rather than long-term consumption focused.

On the other hand, the question of how effective the visualizations will be to increase awareness and how long the users will actually pay attention is something that needs to be explored through long-term user studies. With the excitement of getting a new device, users may initially be more interested in their consumption data than perhaps a few weeks or months later when they might just ignore the frame and solely use the mirror's reflective function. In fact, based on the comments of some participants, the users might be prone to ignore the visualizations, especially the lights, after a while.

> "I am a person who stops caring easily. I would be careful once or twice, but then I would say 'Ehhh. Whatever.' Do you know what I mean? If I get bored of it or something." (P6)

> “In my opinion, our eyes could get used to the lights over time. So because of that, people might automatically ignore that after a while. But a warning once in a while could [take people by surprise].” (P2)

> “I’m not in favour of the lights being used for information because we are already being exposed to a lot of light. Since we are exposed to a lot of light, our susceptibility decreases, and we start to not care. Therefore, a light might not be the best method of delivering information here. Instead, graphic visualizations might be more informative. “ (P4)

User Experience

The presence of an eco-feedback product in the home environment would naturally cause emotions and feelings that wouldn’t occur otherwise. These could be related to how the individual feels about their consumption, how the information is portrayed and how the product fits within their home. It could also be related to how it could affect relationships with people they are living with or people visiting their home, what kinds of feelings may develop in different scenarios when other people are involved. This section is only going to focus on the individual feelings related to the user-product interaction.

When it comes to how the information is portrayed, the product has 4 different methods: units, lights, mirror screen and the dashboard. While some participants did not express any emotions regarding these visualizations at an initial glance, there were some interesting reactions to the physical and ambient visualizations.

For example, one of the participants (P2) expressed that he would be annoyed and distracted that the lights would constantly be on when he is using something in the house. He also believes that they might cause him stress. A few participants mentioned that they would rather be alerted when something is going wrong rather than having to worry about the lights showing what is on constantly.

One of the participants (P7) mentioned that seeing the excessive consumption through the units would make her feel concerned and that she would try to fix the situation immediately. Since the product is designed in a way that change happens slowly over time, the results of users’ efforts will not be immediate. When the participant was asked how she would feel if the situation is not fixed immediately, she expressed that she would feel "pretty frustrated, and anxious and distracted“.

Motivation

During the study, there were some interesting conversations about negative and positive motivators. Some participants expressed that negative motivators such as consequences of their energy use (P1, P8) or the mirror showing that something's off in a room (P7) might motivate them to save energy, even though it could cause stress and frustration. On the other hand, one participant (P2) specifically emphasized his opposition to negative motivators like scolding messages or sad face icons, which have driven him to delete calorie tracking applications in the past.

One participant expressed her appreciation that this product also provides a positive motivator along with informative visualizations:

> "Right now, we wouldn't be happy about anything. We just look at the days that we use a lot of energy. We don't look at the good days, we look at the bad days. But with this, we can look at both positive and negative sides of it." (P9)

On the other hand, one participant (P8) pointed out that the lights could contradict the product's purpose if it's seen as an attractive feature, especially for children. He mentioned that children might want "the mirror to be super shiny", then proceed to turn on all the electronics in the house. This is a similar issue that the Ambient Canvas design faced when the aesthetic appeal of the visualizations motivated the wrong kind of behaviour (Rodgers & Bartram, 2010). A comment about the units from another participant (P3) also potentially points to a similar issue. Although the units were intended to give the feeling that something is off and is supposed to create an urge to fix the issue, the participant expressed that visually asymmetric features actually aesthetically appeal to him, so they would not bother him at all. This is an indicator that these methods might not be as effective for some users to increase their motivation to save energy.

5.5.3. Potential Impact on Social Interactions

Use scenarios involving social interactions provided interesting insights into how the product would affect users' relationships with household members and outsiders visiting their homes. It also helped highlight what kind of privacy issues it could create for the users.

Conflict Between Household Members

During the study, the participants were asked how they would feel if the mirror showed that their room consumed excessive energy while the other household members' rooms were reaching their goals. Many of the participants were in agreement that it would depend on who they are living with and that it could create a conflict if the other person is a roommate with who they are not very close. The reason for the conflict was especially tied to financial concerns, as participants asked if they would be sharing the electricity bill in this scenario before answering the question.

> "I think that could be tricky. And it could even lead to conflict. Because in the end, if there's a mutual agreement of splitting the bill both ways, I won't be surprised if that is going to start bringing in conflict that 'Hey, look, it's your room that's burning more electricity, you should be the one paying more bill.' So that would be a tricky situation, for sure. […] I think I might feel that way too because now I have that information. I know that she is using more. So I would feel that 'Oh, it's unfair. You know, she should be paying more.' " (P7)

> "We are under the assumption […] that we are splitting equally the bill, then yeah, there will definitely be a conversation, right? Because then it would start to get a bit more… more unfair, right?" (P8)

> "Just that it might cause conflicts between people. For example, roommates that are not friends or just anyone that's living together, it might cause conflicts." (P9)

Some participants even expressed or hinted that they would prefer not to have such a mirror if they are in a situation where they are splitting the bill, just to avoid conflict and confrontation.

> "If it is my own unit, with my family, then it's different. If I'm splitting the cost with a contract, where we're saying that we're gonna split it 50/50, then I won't put the mirror up." (P7)

Privacy Concerns

Discussions regarding the social interactions created by the mirror pointed to some potential privacy concerns, both for the people living in the house and for visitors and guests that might see the personal data of the users through the mirror.

Cohabitants

Many participants were in agreement that the product could cause privacy concerns among the household members and that the level of the relationship would determine how they would feel about others seeing their own energy consumption.

The issue seems to be more apparent as the data becomes more detailed. For instance, when participants were asked how they would feel if the people they are living with saw their excessive consumption through the units, they expressed that they wouldn't feel uncomfortable. In fact, some participants thought that it would make others more energy conscious and encourage them to save energy as well. But as the information gets more detailed on the mirror screen and especially in the application, some participants felt uncomfortable about others potentially seeing their activities. Some participants found this to be an issue because of possible conflicts as mentioned before, but some people also mentioned it could feel 'creepy' or they would feel 'stalked'.

> "I mean, it's like data is there for people to learn from so this thing doesn't have your, you know, social insurance number, your personal health information. It's just, it's just data, right? I mean, you know, people need to have to, you know, have... the more access and interest you have in data the better, you know." (P10)

> "Because she... she will say something to me if... she would judge me. […] Or maybe she won't, that's just my guess." (P9)

> "It depends on who I am living with. If I am living with a relative, my sibling, my boyfriend or my friend, then there is no issue. But if I am living with a stranger I wouldn't want to be tracked, yes. For example, let's say I have a roommate and there is no relationship between us. There is no familial or emotional connection. Then I wouldn't want to be tracked, to be honest. Because then I would feel like being stalked." (P4)

> "I think, again, [it] comes down to who I'm living with. If it is a big family, I would not want anybody to know […] that I have my TV on, for example, in my bedroom. So yeah, if it's […] more people, I might get uncomfortable with that amount of information, or them having access to it. I might just lock the application, in that case, to be only accessible by me." (P7)

While some participants thought that the same would apply to a reversed situation (in which they would also have access to other household members' information), some participants mentioned that they would be interested in having that access.

> “I think it's gonna be weird if I start checking on people, a little bit like stalking. Like, in the end, it's way beyond electricity. I'm technically taking a look at what they're doing, like their activity, which is not cool. So yeah, that could be creepy.“ (P7)

> “I would like to see hers, but I don't want her to see mine. […] Just to see how she's doing. […] I think it's better if we don't see each other's energy consumption at the moment, but rather […] at the end of the week. So, not every second, not […] anytime that we want to. It's better if we can see it in total and overall. I think that... that will cause less conflicts than just seeing it anytime you want.” (P9)

On the other hand, some of the participants thought even the most detailed information might not be a cause for privacy concerns.

> “I don’t think there would be something very personal or something that I wouldn’t want them to know about.” (P2)

> “I think it's probably not good for some people who want to like hide what they're doing. Yeah, but for me, it's fine.” (P1)

> “The only thing where I would kind of see that is more delicate is, you know, for example, if you have a condition [that] you need to have a dialysis machine [for] so like maybe that's running [costs super high] and you don't really want to display that part about your health.” (P8)

One participant even expressed that having that kind of detailed access with a person that is close to her is desirable.

> “I actually like that kind of closeness I can share with one person. […] I think if the people who have control over this are someone I can trust and feel connected to, then I'm really open to, like, letting them have the control. Yeah. But if today it's someone that actually just want to monitor and, like, scold me for what I haven't done well, then yeah, that's gonna be a disaster.” (P1)

For one of the participants (P6), the scenario probed more into extreme situations where the user might be able to figure out that the person they are living with was lying about their activities. This was done to test the boundaries of the possible privacy issues. The participant thought that that kind of situation might make people paranoid and that he would refrain from tracking the other person’s activities.

Suggestions from the participants included privacy measures such as having limited access to each other’s information and an admin view for when it is necessary and designing the mirror in a way that differentiates the users so that their screen configurations and information that are shown are different.

Outsiders

Another important point for privacy issues is the concern for outsiders being able to see the private data of the users. With the current design, an outsider can see four types of information from the mirror. The lights, units and ambient visualizations have an abstract way of communicating the information, which requires the person to have knowledge about how the mirror works. Even with that knowledge, the information is generalized and imprecise. The data visualizations on the mirror screen on the other hand have more detailed personal information about the users' energy consumption.

Again, the granularity of the information is a critical part of the privacy issues. Similar to the situation with the cohabitants, the more detailed the information is, the more privacy issues may arise. Hence, several participants pointed out the issue of visitors being able to access the visualizations by simply approaching the mirror.

> "I don't want everybody to be able to see it. So when I'm living by myself, or just with my partner, and I have it in my house, it's perfectly fine. But probably some gesture control or face recognition, I don't know, something like that, so that not everybody has access to that information." (P7)

> "I should be able to access it through the mirror as well, but it shouldn't stay open all the time. I should be able to go there. For example, is it going to scan my eye, ask for a password, recognize my voice, etc.? There should be a security step, then I should access my information. Not everyone should see that." (P4)

It is also an issue that affected the participants' mirror configurations like where they placed the visualizations and how they set up the proximity views.

> "For example, if someone arrives for the first time, when an outsider looks at it I think they will first look at the top and then the bottom. So, for privacy reasons, since I think these will attract less attention so I would put them [at the bottom]. […] From far away… I mean if someone else comes over to my house, they should see the ambient view. It should share the data when I get close. […] I would prefer the mirror screen to show up if someone close to me gets closer to it." (P5)

Even though the ambient and physical visualizations and proximity settings were intended to protect the private information, a few participants saw them as a concern for privacy as well.

> “I wouldn’t want it to attract attention as well. I wouldn’t want a person coming to my home to look at this. […] It should stay quiet, then those [visualizations] should come out when there is a need.” (P4)

> “For example, […] I think the glowing lights or the moving bars will attract other people’s attention. An outsider [seeing that] is not good.” (P5)

Another cause of concern is related to safety and being monitored by the outsiders who might access the information if the data is somehow shared over the internet, for instance with the electricity providers.

> “So everything becomes data, like, every action is monitored. So there probably will be some question about, like, how safe it is. Because I probably won't want, like, others to know my usage data. So if the company is hacked, then my everyday behaviour will be monitored.” (P1)

5.5.4. Summary of Findings

The user study provided intriguing findings about the psychological and social outcomes of bringing energy consumption data into people’s homes. The social consequences especially stood out as a result of this study as the participants stated that they would prefer to place the product in common areas rather than in private spaces in their homes. The design attempted to minimize household conflict and ensure privacy by implementing features such as proximity sensors and abstract visualizations, however, the participant responses demonstrated that these might not be sufficient for some users. Another important finding is that the combination of multiple abstract visualizations could cause confusion and might not support quick and easy comprehension.

The following table outlines the summary of the findings and emergent themes as a result of the user study.

Table 5-3. Summary of findings and emergent themes.

Topics	Sub-topics	Emergent Themes
Placement, Comprehension and Utility	Mirror Placement	• Common and central areas • Accessibility • Multi-functionality as a factor
	Personal Configurations	• Customizability • Personal priorities
	Comprehension and Awareness	• Confusion about abstract visualizations • Importance of metaphors for intuitive visualizations
Outcomes of the Mirror's Presence at Home	Awareness	• Integration into daily activities
	User Experience	• Possible feelings of frustration or stress due to ambient visualizations
	Motivation	• Effects of positive and negative motivators on different users
Potential Impact on Social Interactions	Conflict	• Conflict as a result of shared bills • Level of relationship as a factor
	Privacy	• Data granularity

5.5.5. Design Implications and Redesign Insights

With the feedback from the participants and the insights gathered from this user study, the results provide some design implications for future eco-feedback designs. These insights could be used to improve the current design or they could also be beneficial as a reference point for alternative methods of energy consumption visualization.

Privacy and Conflict

One of the important findings in this study relates to the social interactions between the users and other people around them. The user study highlights the importance of privacy and maintaining healthy social relationships within the household. Considering the fact that this product design publicly visualizes information that is traditionally private and secluded, the participant feedback clearly shows that it could cause some issues regarding data privacy and household conflict. The issue is especially prominent for the data visualizations on the mirror screen and in the application. It could be deduced that the participants were generally satisfied with the amount of ambiguity of data in the physical visualizations in terms of protecting privacy by abstracting the data, especially for people that are unfamiliar with the design.

Based on the participant comments and suggestions, there could be several ways to ensure data protection. One of the methods could be implementing layered views for the visualizations. This could be done by having multiple mirror screen modes in which there are appropriate amounts of detail for information and the deeper levels of the information can only be accessed by the owners. This access could be provided by a feature that recognizes who approaches the mirror. It could be a simple feature such as a hidden button to be pressed, or it could involve more advanced technologies such as voice or face recognition, gesture control or proximity fobs. This of course means that the more advanced technology involved, the higher the price for the product. In other words, a feature that allows interaction with the mirror screen and layered information access could improve the privacy aspect of the design.

Another method applies for data privacy in the application. Instead of having universal access for all the members in the house, the application can have personalized views for each individual to ensure their data privacy. The personalized views could include the private spaces of the individual and the common areas. This feature can be especially useful in situations where multiple roommates are sharing a house and they want to protect the data about when or how much they use their devices in their rooms. Furthermore, with this feature, each member can personalize their own dashboards to prioritize what kind of information they would like to see. In this situation, there could also be an admin view in which all the data of the house could be accessed with the consent of all the members.

Customizations

Observations and interviews from the mirror setup section of the study indicate that each individual has different interests and needs when it comes to the kind of information they want to see on the mirror or in the application. Although the prototype included some examples of visualizations, it was not the representation of the finished end product. Based on the user feedback, more options and customization features can be added to satisfy the needs of all the potential users.

Regarding the visualizations about energy consumption, while some people may prefer concise summaries and easy-to-grasp visualizations on the mirror, others may want to be presented with data graphs and different kinds of visualizations to see more detailed information. When it comes to the widgets unrelated to energy consumption such as time, tasks and news, other options can be included over time based on user demands. From the user study, the most desired widget turned out to be the weather forecast. This is assumed to be related to the dual functionality of the product with its mirror function and its ability to show information on the screen. It is also possible to integrate the energy mirror with other applications to create widgets on the screen, such as personal calendars, habit tracking or other lifestyle applications.

Information Clarity

The study shows that the information clarity of the visualizations in this product design could benefit from some improvements. This applies to both abstract and physical visualizations.

Since the units consist of a unique type of visualization that users are not accustomed to, it turned out to be somewhat confusing for some of the participants to understand and remember their meaning easily. As one participant also suggests, this may be the case due to the fact that the representation of the information is lacking some metaphor for the users to make sense of the information intuitively. Moreover, having multiple abstract visualizations at once causes confusion for the users regarding their meaning and the relationship between the visualizations. Therefore, limiting the number of unfamiliar visualization techniques might be more useful to lower the effort to learn and understand what the visualizations are trying to communicate.

A similar comment about metaphors was made for the ambient visualizations on the mirror screen for the achievements as well. A few participants suggested adding visuals that are more related to the environment, such as trees and forests that might correlate to users' motivation to save energy.

As for the digital visualizations, since the participants were more familiar with this type of visual communication, the feedback for improvements only consist of small alterations in the application to improve the user experience. These alterations include descriptions for the icons and numerical values for the bar graphs.

Marketing and Appeal

During the interviews, the discussions also included what would encourage the users to purchase a product like this and the marketing challenges that this product may have. One of the concerns is that people might not be inclined to purchase the product without enough motivation to save energy in the first place. Many of the participants also stated that the price would be a crucial contributor to their decision. Therefore, designers should consider the price of the materials and production during the process as well. Even though the additions of newer technologies may increase the marketing appeal, the price should be appropriate for the performance of the product.

On the other hand, some of the participants mentioned that the integration of the product with the smart home systems might also be a compelling feature for them to purchase such a device. Mentioned features included the connection with existing smart home systems such as Alexa or Google Home, as well as speakers and other entertainment-related features.

It should also be acknowledged that the product itself also consumes energy and costs the users to purchase it. Depending on what the users' motivation is and the amount that the product costs and consumes, this could create a contradiction for the product's purpose. The price aspect might make the product unsuitable for every household since it contains a smart mirror which has a higher price than many people are able or willing to pay for a mirror that they intend to use in their house. Yet, the physical visualization properties of the product without the digital aspect could be applied at a lower cost by simply removing the screen and changing the two-way mirror to a regular mirror. In addition, this will also lower the amount of energy the mirror consumes daily. Although the additional features and technologies might increase the marketing appeal of the product, for the energy-saving purpose and to keep the product at a low cost for people who are trying to save money by saving energy, it might be more consistent with the product's intent to keep its design more minimal and to the point.

Alternative Uses

Another topic of conversation during the interviews revolved around the possible alternative situations that this design could be used in. One participant (P4) argued that a product like this would be more useful in commercial areas instead of residential settings. She points out that in commercial buildings such as hotels, airports, factories and hospitals, energy consumption is much higher than in residential buildings and therefore a product that is designed to save energy would be more effective in those areas. However, the mirror function of the design might not be appropriate in some of these public settings. In that case, designers can make use of other ways of communicating the energy consumption information using different objects and structures instead. This could not only lead to energy savings but also raise public awareness about how much energy is used in these commercial buildings.

Chapter 6. Conclusion and Future Work

Eco-feedback design has been a topic of interest in the HCI field in recent years, especially due to climate change and environmental concerns that have been increasing over time. The common goal of the eco-feedback designs has been to inform users about their consumption and encourage them to take action and conserve energy and water resources. There are several examples of projects and designs in the literature and the commercial market that experiment with different methods to achieve this goal. This project acts as another step forward in understanding how product design can contribute to energy savings at home. The thesis went through the thought process behind the design decisions, explained the features of the energy mirror design and shared the insights that were gathered from the user feedback for the prototype in the user study.

The product design in this project aimed to address the issues that exist in the current eco-feedback solutions. As the previous studies have shown, one of the main issues is the effort and time it requires for the users to access and comprehend the information about their energy consumption. Many of the current eco-feedback solutions require users to log in to a website or application and actively seek information. Previous work also includes visualization designs that tackle this problem by creating a constant ambient awareness. In-home displays are also designed to lower the effort to access information. This project took the concept a step further by integrating the information into an object that people use daily in their lives instead of a separate device that specifically serves this function.

Another important concern is the design's impact on users' energy consumption behaviour. This includes its ability to provide actionable information in a timely manner and how it can motivate users to save energy during their daily activities. Having an ambient awareness of the energy consumption at home allows users to have an idea about what devices in their home consume excessive energy and make informed decisions to prevent it. The product design in this project took inspiration from previous ambient visualization designs but takes a slightly different approach to how the information is portrayed. It made use of physical visualizations that can exist in the environment even when the digital screens are off. The goal of the design is to become a part of the users' daily routines and involve the users in the process with the slow technology aspect rather than simply providing a report on their consumption.

When it comes to the motivation to save energy, many different approaches can be seen in the literature from monetary incentives to negative motivators that highlight the environmental consequences of the consumption. However, for some users, negative motivators may create the opposite effect and cause feelings of guilt and discouragement for the users. It can eventually lead to them getting rid of the source of these emotions. With this knowledge, this project focused more on neutral motivators that aim to create awareness and positive motivators that encourage users by rewarding their energy-conserving behaviour. The ambient visualizations on the mirror screen that symbolize the users' energy-saving achievements are an example of the motivators used in this design.

As a result, the prototype of the product design was built to get user feedback and discover its strengths, weaknesses and improvement opportunities. The user study involved use scenarios and simulated interactions through a remotely conducted interview. The results provided some insights for any future design work related to this topic.

6.1. Contributions

This research study explored the outcomes of materializing an abstract notion through product design. Energy consumption is an invisible concept in our daily lives and the traditional communication methods for this information usually consist of data visualizations on paper or screens on our digital devices. The product design in this research study brings this information into users' physical environment and integrates it into people's daily activities at home through already existing everyday objects.

The main contributions of this research study to the energy feedback design field are the energy mirror design and the design implications acquired from the user study. The results of the study reveal the potential benefits and consequences of the energy mirror design in the residential context.

Although there aren't concrete pieces of evidence for the benefits, based on the user feedback, the energy mirror allows energy consumption feedback to be integrated into people's daily activities and provides an opportunity to raise awareness for the members of the house about their energy use. The participants expressed that the product would be helpful to make informed decisions while trying to save energy.

The potential outcomes discovered during the user study will be helpful for improving the design to avoid unwanted consequences to happen. A significant part of the results deals with the social interactions induced by the product. This study highlights the importance of privacy and avoiding possible conflicts for designers that aim to explore energy feedback through ambient and physical visualizations, while also making sure to make them clear and easy to comprehend.

6.2. Future Work

This study acts as a step forward in researching how effective physical visualizations can be for supporting energy savings at home. Future work opportunities may include redesigns and improvements for this concept design, alternative user testing studies and exploring different objects, surfaces or materials to carry out a similar purpose.

As the user study in this project was conducted in a remote setting, the full potential of the user feedback could not be achieved. Furthermore, the long term effects of this design in a setting where users actually live with the product for a while need to be explored to gather more extensive insights, especially to measure the effectiveness of the visualizations in terms of how they affect motivation, how well they inform and raise awareness.

A promising aspect to explore could also be the product's role as a guide for saving energy. The current design provides data visualizations in different forms and personalized advice for users to conserve energy in their houses based on their consumption habits. Exploring how far the guidance of an eco-feedback design could go might yield interesting insights into its effectiveness. This can also include automation and setting up modes for different situations. For example, the system could turn devices on and off based on the modes that the users select (such as low energy mode, out of the house mode, etc.) or based on the time of day.

The chosen product to communicate the energy consumption feedback was a mirror in this project, but there are many other possibilities to explore. An example is the Ambient Canvas, which was the inspiration for this project, which utilized a kitchen backsplash (Rodgers & Bartram, 2010). Early idea generations for this project included coffee tables as well but this idea was scrapped when the design explorations couldn't support both the function of the surface and the energy consumption visualizations. Future work could delve into improving the current design or taking advantage of other possible vessels in the residential settings.

Lastly, designers can also consider a similar approach in different settings instead of private homes. These could include commercial and public buildings in which higher amounts of energy are consumed. It could also serve as an educational opportunity for children if a similar approach is taken in schools. Visualizing energy use can raise early awareness for children and encourage building better consumption habits for the future.

References

Abrahamse, W., & Steg, L. (2009). How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *Journal of Economic Psychology*, *30*(5), 711–720. https://doi.org/10.1016/j.joep.2009.05.006

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology*, *25*(3), 273–291. https://doi.org/10.1016/j.jenvp.2005.08.002

Allcott, H., & Rogers, T. (2014). The short-run and long-run effects of behavioral interventions: Experimental evidence from energy conservation. *American Economic Review*, *104*(10), 3003–3037.

Antle, A. N., Droumeva, M., & Ha, D. (2009). Hands on what? Comparing children's mouse-based and tangible-based interaction. *Proceedings of the 8th International Conference on Interaction Design and Children*, 80–88.

Auffhammer, M., & Wolfram, C. D. (2014). Powering up China: Income distributions and residential electricity consumption. *American Economic Review*, *104*(5), 575–580.

Barreto, M., Karapanos, E., & Nunes, N. (2013). Why don't families get along with eco-feedback technologies?: A longitudinal inquiry. *Proceedings of the Biannual Conference of the Italian Chapter of SIGCHI on - CHItaly '13*, 1–4. https://doi.org/10.1145/2499149.2499164

Bartram, L. (2015). Design Challenges and Opportunities for Eco-Feedback in the Home. *IEEE Computer Graphics and Applications*, *35*(4), 52–62. https://doi.org/10.1109/MCG.2015.69

Bartram, L., Rodgers, J., & Muise, K. (2010). Chasing the Negawatt: Visualization for Sustainable Living. *IEEE Computer Graphics and Applications*, *30*(3), 8–14. https://doi.org/10.1109/MCG.2010.50

Bartram, L., Rodgers, J., & Woodbury, R. (2011). Smart Homes or Smart Occupants? Supporting Aware Living in the Home. In P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, & M. Winckler (Eds.), *Human-Computer Interaction – INTERACT 2011* (Vol. 6947, pp. 52–64). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-23771-3_5

Bateman, S., Mandryk, R. L., Gutwin, C., Genest, A., McDine, D., & Brooks, C. (2010). Useful junk? The effects of visual embellishment on comprehension and memorability of charts. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2573–2582.

BC Hydro. (2019, April 29). *HydroHome app paves the way for the smart home*. https://www.bchydro.com/news/conservation/2019/hydrohome-trial.html

BC Hydro. (2020). *Understanding your electricity use*. https://www.bchydro.com/accounts-billing/rates-energy-use/rates-energy-use.html

Becker, L. J. (1978). Joint effect of feedback and goal setting on performance: A field study of residential energy conservation. *Journal of Applied Psychology*, *63*(4), 428.

Black, R., Davidson, P., & Retra, K. (2009). *Facilitating energy saving behaviours among university student residents* (Vol. 25).

Bord, R. J., O'connor, R. E., & Fisher, A. (2000). In what sense does the public need to understand global climate change? *Public Understanding of Science*, *9*(3), 205–218.

Chetty, M., Brush, A. J., Meyers, B., & Johns, P. (2009). It's not easy being green: Understanding home computer power management. *CHI '09: Proceedings of the 27th International Conference on Human Factors in Computing Systems*. http://portal.acm.org/citation.cfm?id=1518701.1518860

Chetty, M., Tran, D., & Grinter, R. E. (2008). Getting to green: Understanding resource consumption in the home. *Proceedings of the 10th International Conference on Ubiquitous Computing*, 242–251.

Creswell, J. W. (2007). *Qualitative inquiry & research design: Choosing among five approaches* (2nd ed). Sage Publications.

Dam, R. F. (2021). *5 Stages in the Design Thinking Process*. The Interaction Design Foundation. https://www.interaction-design.org/literature/article/5-stages-in-the-design-thinking-process

Darby, S. (2008). Energy feedback in buildings: Improving the infrastructure for demand reduction. *Building Research & Information*, *36*(5), 499–508.

Darby, S. (2010). Literature review for the energy demand research project. *London: Ofgem (Office of Gas and Electricity Markets)*.

Davidoff, S., Lee, M. K., Dey, A. K., & Zimmerman, J. (2007). Rapidly Exploring Application Design Through Speed Dating. In J. Krumm, G. D. Abowd, A. Seneviratne, & T. Strang (Eds.), *UbiComp 2007: Ubiquitous Computing* (Vol.

4717, pp. 429–446). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74853-3_25

Ehrhardt-Martinez, K., Donnelly, K. A., & Laitner, S. (2010). *Advanced metering initiatives and residential feedback programs: A meta-review for household electricity-saving opportunities*.

Enerdata. (2020). *Global Energy Trends 2020 | Enerdata*. https://www.enerdata.net/publications/reports-presentations/world-energy-trends.html

Ersson, E., & Pyrko, J. (2009). El-info via digitala kanaler. Fallstudie 1" Min elförbrukning" hos Skånska Energi.(Information via digital channels. Case study 1" My electricity use" at Skanska Energy). Lund University. *Energy Sciences, LUTMDN/TMHP–09/3039–SE*.

Fällman, D. (2004). Design oriented-research versus Research-oriented Design. *Workshop Paper, CHI 2004 Workshop on Design and HCI, Conference on Human Factors in Computing Systems, CHI*, 24–29.

Fallman, D. (2007). Why Research-Oriented Design Isn't Design-Oriented Research: On the Tensions Between Design and Research in an Implicit Design Discipline. *Knowledge, Technology & Policy*, *20*(3), 193–200. https://doi.org/10.1007/s12130-007-9022-8

Fehrenbacher, K. (2011a, June 26). *5 reasons Google PowerMeter didn't take off*. Gigaom. https://gigaom.com/2011/06/26/5-reasons-google-powermeter-didnt-take-off/

Fehrenbacher, K. (2011b, July 1). *5 reasons why Microsoft Hohm didn't take off*. Gigaom. https://gigaom.com/2011/07/01/5-reasons-why-microsoft-hohm-didnt-take-off/

Fischer, C. (2008). Feedback on household electricity consumption: A tool for saving energy? *Energy Efficiency*, *1*(1), 79–104. https://doi.org/10.1007/s12053-008-9009-7

Froehlich, J., Findlater, L., & Landay, J. (2010). The design of eco-feedback technology. *Proceedings of the 28th International Conference on Human Factors in Computing Systems - CHI '10*, 1999. https://doi.org/10.1145/1753326.1753629

Froehlich, J., Patel, S., Landay, J. A., Findlater, L., Ostergren, M., Ramanathan, S., Peterson, J., Wragg, I., Larson, E., Fu, F., & Bai, M. (2012). The design and evaluation of prototype eco-feedback displays for fixture-level water usage data. *Proceedings of the 2012 ACM Annual Conference on Human Factors in Computing Systems - CHI '12*, 2367. https://doi.org/10.1145/2207676.2208397

Gaskell, G., Ellis, P., & Pike, R. (1982). *The Energy Literate Consumer: The Effects of Consumption Feedback and Information on Beliefs, Knowledge and Behavior." Department of Social Psychology, LSE*.

Gatersleben, B., & Vlek, C. (1998a). Household consumption, quality of life, and environmental impacts: A psychological perspective and empirical study. *Green Households? Domestic Consumers, Environment, and Sustainability*, 141–183.

Gatersleben, B., & Vlek, C. (1998b). Household consumption, quality of life, and environmental impacts: A psychological perspective and empirical study. *Green Households? Domestic Consumers, Environment, and Sustainability*, 141–183.

Geller, E. S. (2002). The challenge of increasing proenvironment behavior. *Handbook of Environmental Psychology*, *2*, 525–540.

Get Started with Design Thinking. (n.d.). Stanford d.School. Retrieved February 13, 2022, from https://dschool.stanford.edu/resources/getting-started-with-design-thinking

Google.org. (2011). *Google PowerMeter: A Google.org Project*. http://www.google.com/powermeter/about/

Grosse-Hering, B., Mason, J., Aliakseyeu, D., Bakker, C., & Desmet, P. (2013). Slow design for meaningful interactions. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 3431. https://doi.org/10.1145/2470654.2466472

Gungut, M. (2019). *Electricity Bill of the Workplace Artvin* [Digital Image]. https://www.shutterstock.com/image-photo/turkey-electricity-bill-workplace-1277864539

Guta, M. (2017, August 16). 20 Mobile Apps to Help You Reduce Energy Costs. *Small Business Trends*. https://smallbiztrends.com/2017/08/mobile-apps-to-help-you-reduce-energy-costs.html

Hallnäs, L., & Redström, J. (2001). Slow Technology – Designing for Reflection. *Personal and Ubiquitous Computing*, *5*(3), 201–212. https://doi.org/10.1007/PL00000019

Hargreaves, T., Nye, M., & Burgess, J. (2010). Making energy visible: A qualitative field study of how householders interact with feedback from smart energy monitors. *Energy Policy*, *38*(10), 6111–6119.

Holmes, T. G. (2007). Eco-visualization: Combining art and technology to reduce energy consumption. *Proceedings of the 6th ACM SIGCHI Conference on Creativity & Cognition - C&C '07*, 153. https://doi.org/10.1145/1254960.1254982

Huang, D., Tory, M., & Bartram, L. (2016). A Field Study of On-Calendar Visualizations [Application/pdf]. *Proceedings of Graphics Interface 2016*, *Victoria*, 8 pages, 610.40 kB. https://doi.org/10.20380/GI2016.03

Huang, M. L., Nguyen, Q. V., & Zhang, K. (Eds.). (2010). *Visual Information Communication*. Springer US. https://doi.org/10.1007/978-1-4419-0312-9

IEA. (2008). *Worldwide Trends in Energy Use and Efficiency*. IEA. https://www.iea.org/reports/worldwide-trends-in-energy-use-and-efficiency

IEA. (2020a). *Data and statistics*. IEA. https://www.iea.org/reports/energy-transitions-indicators

IEA. (2020b). *Data and statistics*. IEA. https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20consumption&indicator=ElecConsBySector

IEA. (2020c, April 23). *CO2 emissions statistics – Data services*. IEA. https://www.iea.org/subscribe-to-data-services/co2-emissions-statistics

Jafarinaimi, N., Forlizzi, J., Hurst, A., & Zimmerman, J. (2005). Breakaway: An ambient display designed to change human behavior. *CHI'05 Extended Abstracts on Human Factors in Computing Systems*, 1945–1948.

Jansen, Y. (2014). *Physical and tangible information visualization*. Université Paris Sud - Paris XI.

Kantola, S. J., Syme, G. J., & Nesdale, A. R. (1983). The effects of appraised severity and efficacy in promoting water conservation: An informational analysis. *Journal of Applied Social Psychology*, *13*(2), 164–182.

Katzev, R. D., & Johnson, T. R. (1983). A social-psychological analysis of residential electricity consumption: The impact of minimal justification techniques. *Journal of Economic Psychology*, *3*(3–4), 267–284.

Katzev, R. D., & Johnson, T. R. (1987). *Promoting energy conservation: An analysis of behavioral research*.

Kim, T., Hong, H., & Magerko, B. (2010). Design requirements for ambient display that supports sustainable lifestyle. *Proceedings of the 8th ACM Conference on Designing Interactive Systems*, 103–112.

Kohlenberg, R., Phillips, T., & Proctor, W. (1976). A behavioral analysis of peaking in residential electrical-energy consumers. *Journal of Applied Behavior Analysis*, *9*(1), 13–18.

Korosec, K. (2011, June 24). *Why Google's Home-Energy Product PowerMeter Failed*. http://www.cbsnews.com/8301-505123_162-43045731/why-googles-home-energy-product-powermeter-failed/

Kosara, R., Healey, C. G., Interrante, V., Laidlaw, D. H., & Ware, C. (2003). *Thoughts on User Studies: Why, How, and When*. 7.

LaMonica, M. (2011, June 30). *Microsoft kills Hohm energy app*. CNET. https://www.cnet.com/news/microsoft-kills-hohm-energy-app/

Laustsen, J. (2008). Energy efficiency requirements in building codes, energy efficiency policies for new buildings. IEA Information Paper. *Support of the G8 Plan of Action*.

Li, D. H., Yang, L., & Lam, J. C. (2012). Impact of climate change on energy use in the built environment in different climate zones–a review. *Energy*, *42*(1), 103–112.

Lindenberg, S., & Steg, L. (2007). Normative, gain and hedonic goal frames guiding environmental behavior. *Journal of Social Issues*, *63*(1), 117–137.

Liu, J. (2016, February 4). Visualizing the 4 Essentials of Design Thinking. *Good Design*. https://medium.com/good-design/visualizing-the-4-essentials-of-design-thinking-17fe5c191c22

Liu, T., Ding, X., Liu, P., Lu, T., & Gu, N. (2016). ArchiExpression: A Physical Eco-Feedback Display in an Outdoor Campus Space of China. *Proceedings of the Fourth International Symposium on Chinese CHI - ChineseCHI2016*, 1–10. https://doi.org/10.1145/2948708.2948711

Locke, E. A., & Latham, G. P. (2002). Building a practically useful theory of goal setting and task motivation: A 35-year odyssey. *American Psychologist*, *57*(9), 705.

Makonin, S., Bartram, L., & Popowich, F. (2013). A Smarter Smart Home: Case Studies of Ambient Intelligence. *IEEE Pervasive Computing*, *12*(1), 58–66. https://doi.org/10.1109/MPRV.2012.58

Mankoff, J., Dey, A. K., Hsieh, G., Kientz, J., Lederer, S., & Ames, M. (2003). Heuristic Evaluation of Ambient Displays. *NEW HORIZONS*, *5*, 8.

McCalley, L. T., & Midden, C. J. (2002). Energy conservation through product-integrated feedback: The roles of goal-setting and social orientation. *Journal of Economic Psychology*, *23*(5), 589–603.

Meier, A., & Nordman, B. (2008). *Low Power Mode Energy Use in California Homes*. 10.

Meinel, C., Leifer, L., & Plattner, H. (Eds.). (2011a). *Design Thinking*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-13757-0

Meinel, C., Leifer, L., & Plattner, H. (Eds.). (2011b). *Design Thinking*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-13757-0

Midden, C. J., Meter, J. F., Weenig, M. H., & Zieverink, H. J. (1983). Using feedback, reinforcement and information to reduce energy consumption in households: A field-experiment. *Journal of Economic Psychology*, *3*(1), 65–86.

Moere, A. V., & Patel, S. (2009). The physical visualization of information: Designing data sculptures in an educational context. In *Visual information communication* (pp. 1–23). Springer.

Mountain, D. (2007). Real-time feedback and residential electricity consumption: British Columbia and Newfoundland and Labrador pilots. *Mountain Economic Consulting and Associates Inc*.

Mullai, B. D., & Sivasamy, R. (2017). Impact of vampire power and its reduction techniques—A review. *2017 International Conference on Intelligent Computing and Control Systems (ICICCS)*, 404–405. https://doi.org/10.1109/ICCONS.2017.8250752

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Abd. Majid, M. Z. (2015). A global review of energy consumption, CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries). *Renewable and Sustainable Energy Reviews*, *43*, 843–862. https://doi.org/10.1016/j.rser.2014.11.066

Neustaedter, C., Bartram, L., & Mah, A. (2013). Everyday activities and energy consumption: How families understand the relationship. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 1183. https://doi.org/10.1145/2470654.2466153

Nexia™. (n.d.). *Nexia | Smart Home Automation System | Comfort First*. Nexia™. Retrieved July 14, 2020, from https://www.nexiahome.com/

Odom, W., Banks, R., Durrant, A., Kirk, D., & Pierce, J. (2012). Slow technology: Critical reflection and future directions. *Proceedings of the Designing Interactive Systems Conference on - DIS '12*, 816. https://doi.org/10.1145/2317956.2318088

Odom, W., Pierce, J., & Roedl, D. (2008). *Social Incentive & Eco-Visualization Displays: Toward Persuading Greater Change in Dormitory Communities*. 3.

Odom, W., Pierce, J., Stolterman, E., & Blevis, E. (2009). Understanding why we preserve some things and discard others in the context of interaction design. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1053–1062.

Odom, W. T., Sellen, A. J., Banks, R., Kirk, D. S., Regan, T., Selby, M., Forlizzi, J. L., & Zimmerman, J. (2014). Designing for slowness, anticipation and re-visitation: A long term field study of the photobox. *Proceedings of the 32nd Annual ACM*

Conference on Human Factors in Computing Systems - CHI '14, 1961–1970. https://doi.org/10.1145/2556288.2557178

Odom, W., Zimmerman, J., Davidoff, S., Forlizzi, J., Dey, A. K., & Lee, M. K. (2012). A fieldwork of the future with user enactments. *Proceedings of the Designing Interactive Systems Conference on - DIS '12*, 338. https://doi.org/10.1145/2317956.2318008

Pablo-Romero, M. del P., Pozo-Barajas, R., & Yñiguez, R. (2017). Global changes in residential energy consumption. *Energy Policy*, *101*, 342–352. https://doi.org/10.1016/j.enpol.2016.10.032

Pallak, M. S., & Cummings, W. (1976). Commitment and voluntary energy conservation. *Personality and Social Psychology Bulletin*, *2*(1), 27–30.

Petersen, J. E., Shunturov, V., Janda, K., Platt, G., & Weinberger, K. (2007). Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. *International Journal of Sustainability in Higher Education*.

Petersen, M. G., Iversen, O. S., Krogh, P. G., & Ludvigsen, M. (2004). Aesthetic interaction: A pragmatist's aesthetics of interactive systems. *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*, 269–276.

Pierce, J., Odom, W., & Blevis, E. (2008). Energy aware dwelling: A critical survey of interaction design for eco-visualizations. *Proceedings of the 20th Australasian Conference on Computer-Human Interaction Designing for Habitus and Habitat - OZCHI '08*, 1. https://doi.org/10.1145/1517744.1517746

Plattner, H., Meinel, C., & Leifer, L. (Eds.). (2016). *Design Thinking Research*. Springer International Publishing. https://doi.org/10.1007/978-3-319-19641-1

PPL Electric Utilities. (2020). *Understanding Your Electric Bill*. https://www.pplelectric.com/master-pages/sample-bill.aspx

Quintal, F., Jorge, C., Nisi, V., & Nunes, N. (2016). Watt-I-See: A Tangible Visualization of Energy. *Proceedings of the International Working Conference on Advanced Visual Interfaces - AVI '16*, 120–127. https://doi.org/10.1145/2909132.2909270

Ritchie, H., & Roser, M. (2014). Energy. *Our World in Data*. https://ourworldindata.org/energy

Rodgers, J., & Bartram, L. (2010). ALIS: An interactive ecosystem for sustainable living. *Proceedings of the 12th ACM International Conference Adjunct Papers on Ubiquitous Computing - Ubicomp '10*, 421. https://doi.org/10.1145/1864431.1864467

Rodgers, J., & Bartram, L. (2011). Exploring Ambient and Artistic Visualization for Residential Energy Use Feedback. *IEEE Transactions on Visualization and Computer Graphics*, *17*(12), 2489–2497. https://doi.org/10.1109/TVCG.2011.196

Rogers, Y., Hazlewood, W. R., Marshall, P., Dalton, N., & Hertrich, S. (2010). Ambient influence: Can twinkly lights lure and abstract representations trigger behavioral change? *Proceedings of the 12th ACM International Conference on Ubiquitous Computing*, 261–270.

Ross, J. P., & Meier, A. (2001). Whole-House Measurements of Standby Power Consumption. In P. Bertoldi, A. Ricci, & A. de Almeida (Eds.), *Energy Efficiency* *in Household Appliances and Lighting* (pp. 278–285). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-56531-1_33

Rossini, G. (2009). Hydro One: In Home Real Time Display: Customer Feedback from a 30,000 Unit Deployment. *Home Energy Displays Conference, Orlando*, *2*.

Russo, B. (2010). Shoes, Cars, and Other Love Stories: Investigating The Experience of Love for Products [Urn:NBN:nl:ui:24-uuid:fb4b87ce-ff66-44f3-9c81-0e7c5bfa7c78, VSSD]. In *None (EN)*. http://resolver.tudelft.nl/uuid:fb4b87ce-ff66-44f3-9c81-0e7c5bfa7c78

Ryon, B. (2009, June 24). Microsoft Hohm Helps Consumers Save Money and Energy. *Stories*. https://news.microsoft.com/2009/06/24/microsoft-hohm-helps-consumers-save-money-and-energy/

Schipper, L., Bartlett, S., Hawk, D., & Vine, E. (1989). Linking life-styles and energy use: A matter of time? *Annual Review of Energy*, *14*(1), 273–320.

Schmandt-Besserat, D. (1996). *How writing came about* (1st abridged ed). University of Texas Press.

Schuitema, G., & Steg, L. (2005). Percepties van energieverbruik van huishoudelijke apparaten. In *Ontwikkelingen in het marktonderzoek, jaarboek 2005* (pp. 165–180). De Vrieseborch.

Schwartz, S. H. (1977). Normative influences on altruism. *Advances in Experimental Social Psychology*, *10*(1), 221–279.

Singhal, S., Odom, W., Bartram, L., & Neustaedter, C. (2017). Time-Turner: Data Engagement Through Everyday Objects in the Home. *Proceedings of the 2016*

ACM Conference Companion Publication on Designing Interactive Systems - DIS ’17 Companion, 72–78. https://doi.org/10.1145/3064857.3079122

Skog, T., Ljungblad, S., & Holmquist, L. E. (2003). Between aesthetics and utility: Designing ambient information visualizations. *IEEE Symposium on Information Visualization 2003 (IEEE Cat. No. 03TH8714)*, 233–240.

Slavin, R. E., Wodarski, J. S., & Blackburn, B. L. (1981). A group contingency for electricity conservation in master-metered apartments. *Journal of Applied Behavior Analysis*, *14*(3), 357–363.

Staats, H., Harland, P., & Wilke, H. A. (2004). Effecting durable change: A team approach to improve environmental behavior in the household. *Environment and Behavior*, *36*(3), 341–367.

Standby Power Summary Table » Standby Power. (n.d.). Standby Power. Retrieved July 1, 2020, from https://standby.lbl.gov/data/summary-table/

Statista Research Department. (2020, March 3). *Smart home—Statistics & Facts*. Statista. https://www.statista.com/topics/2430/smart-homes/

Steg, L. (2008). Promoting household energy conservation. *Energy Policy*, *36*(12), 4449–4453. https://doi.org/10.1016/j.enpol.2008.09.027

Stern, P. C., & Dietz, T. (1994). The value basis of environmental concern. *Journal of Social Issues*, *50*(3), 65–84.

Strengers, Y. A. A. (2011). Designing eco-feedback systems for everyday life. *Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems - CHI ’11*, 2135. https://doi.org/10.1145/1978942.1979252

Suganthi, L., & Samuel, A. A. (2012). Energy models for demand forecasting—A review. *Renewable and Sustainable Energy Reviews*, *16*(2), 1223–1240.

Sun, M. (2014). *Exploring Aesthetic Visualization for Promoting Consumer Energy Conservation*.

Sun, M., & Bartram, L. (2014). *Energy Conservation Game: Exploring Alternative Visualizations for Residential Energy Use*. 4.

The Nielsen Company. (2018, October 16). *Sustainability Sells: Linking Sustainability Claims to Sales*. https://www.nielsen.com/us/en/insights/article/2018/sustainability-sells-linking-sustainability-claims-to-sales

Ullmer, B., & Ishii, H. (2000). Emerging frameworks for tangible user interfaces. *IBM Systems Journal*, *39*(3.4), 915–931.

Ullmer, B., Kim, E., Kilian, A., Gray, S., & Ishii, H. (2001). Strata/ICC: physical models as computational interfaces. *CHI'01 Extended Abstracts on Human Factors in Computing Systems*, 373–374.

U.S. Energy Information Administration (EIA). (2019a, April 8). *Use of energy in homes*. https://www.eia.gov/energyexplained/use-of-energy/homes.php

U.S. Energy Information Administration (EIA). (2019b, May 9). *Electricity use in homes*. https://www.eia.gov/energyexplained/use-of-energy/electricity-use-in-homes.php

U.S. Energy Information Administration (EIA). (2020, April). *Use of energy in explained*. https://www.eia.gov/energyexplained/use-of-energy/

van Dam, S. S., Bakker, C. A., & Van Hal, J. D. M. (2010). Home energy monitors: Impact over the medium-term. *Building Research & Information*, *38*(5), 458–469.

Van Houwelingen, J. H., & Van Raaij, W. F. (1989). The effect of goal-setting and daily electronic feedback on in-home energy use. *Journal of Consumer Research*, *16*(1), 98–105.

Verschuren, P., & Hartog, R. (2005). Evaluation in Design-Oriented Research. *Quality & Quantity*, *39*(6), 733–762. https://doi.org/10.1007/s11135-005-3150-6

Wilhite, H., & Ling, R. (1995). Measured energy savings from a more informative energy bill. *Energy and Buildings*, *22*(2), 145–155.

Woodbury, R., Bartram, L., Cole, R., Hyde, R., Macleod, D., & Marques, D. (2008). *Buildings and climate solutions*. Pacific Institute for Climate Solutions, University of Victoria.

Woodbury, R. F., Bartram, L., Cole, R., Hyde, R., Macleod, D., Marques, D., Mueller, T., & Vanier, D. (2008). *Buildings and Climate Solutions*. Pacific Institute for Climate Solutions, University of Victoria. http://www.sfu.ca/ccirc/workshop-08_11/Sustainable_Buildings.pdf

Wu, A. (2010). Tangible visualization. *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*, 317–318.

Wu, Y. (2018). *Exploring Non-pragmatic Visualizations for A Residential Water Conservation Game*.

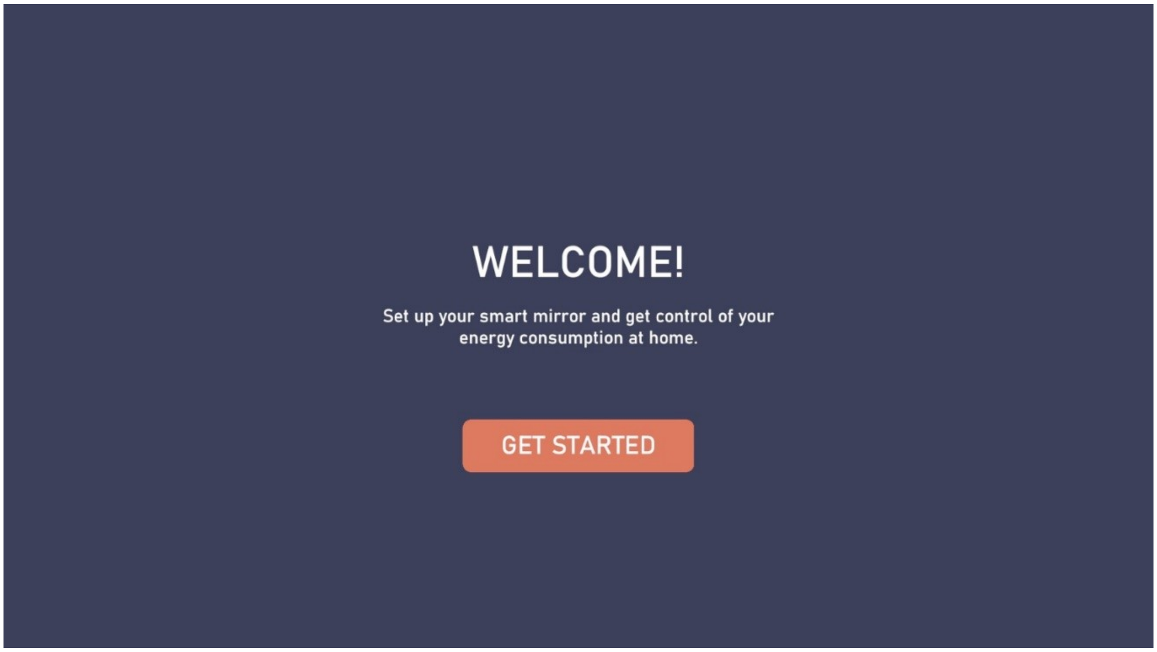
Yau, Y. H., & Hasbi, S. (2013). A review of climate change impacts on commercial buildings and their technical services in the tropics. *Renewable and Sustainable Energy Reviews*, *18*, 430–441. https://doi.org/10.1016/j.rser.2012.10.035

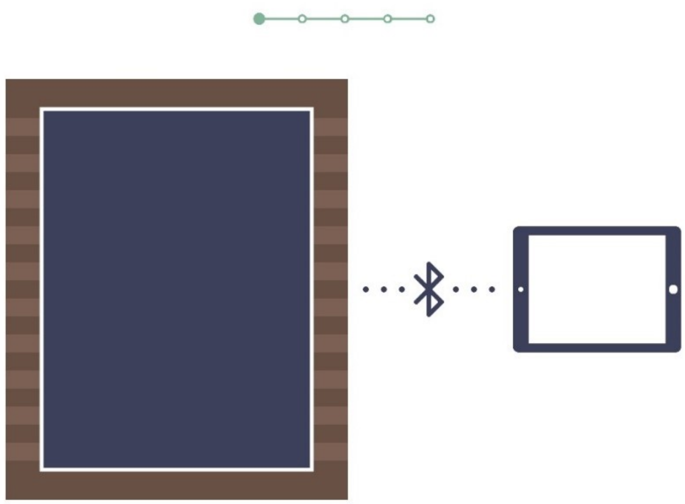
Zhao, J., & Moere, A. V. (2008). Embodiment in data sculpture: A model of the physical visualization of information. *Proceedings of the 3rd International Conference on*

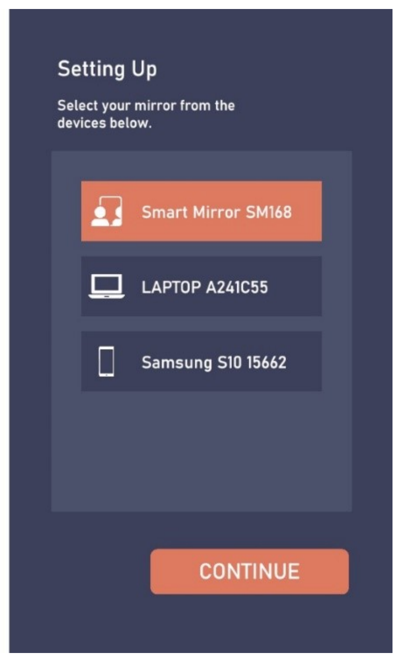
Digital Interactive Media in Entertainment and Arts - DIMEA '08, 343.

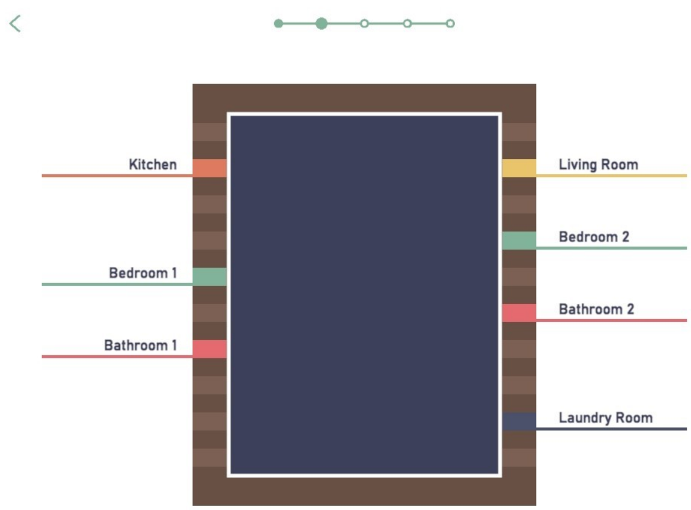
https://doi.org/10.1145/1413634.1413696

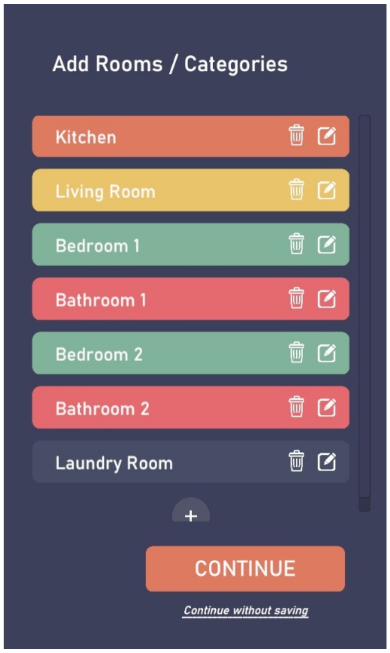
Appendix. Application Prototype

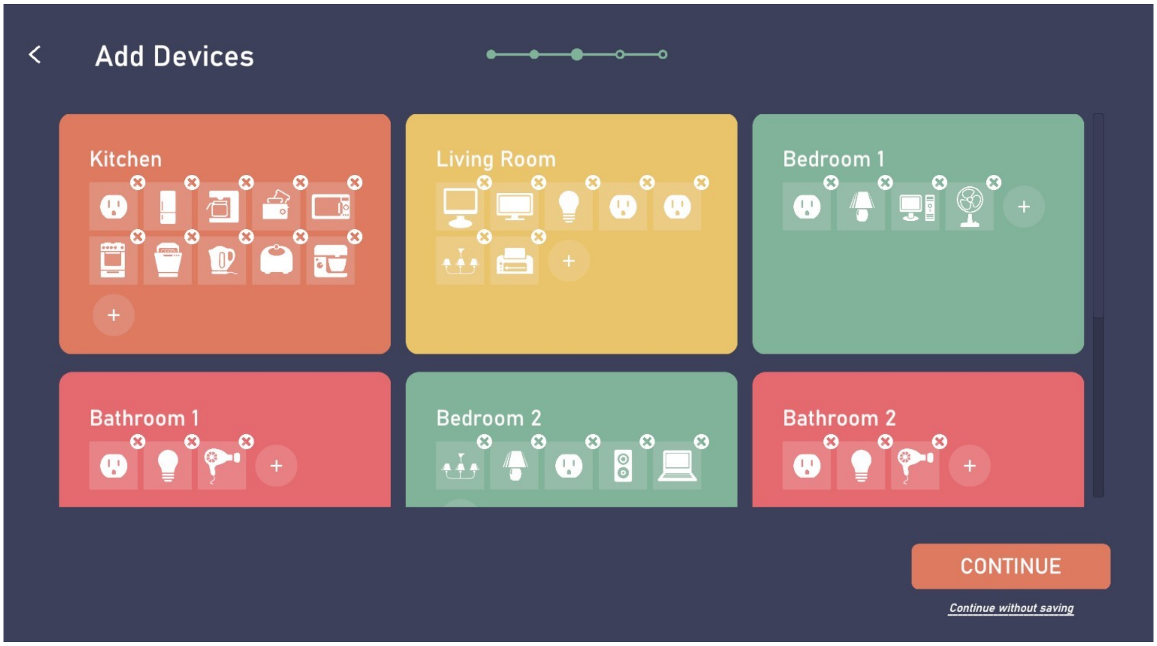


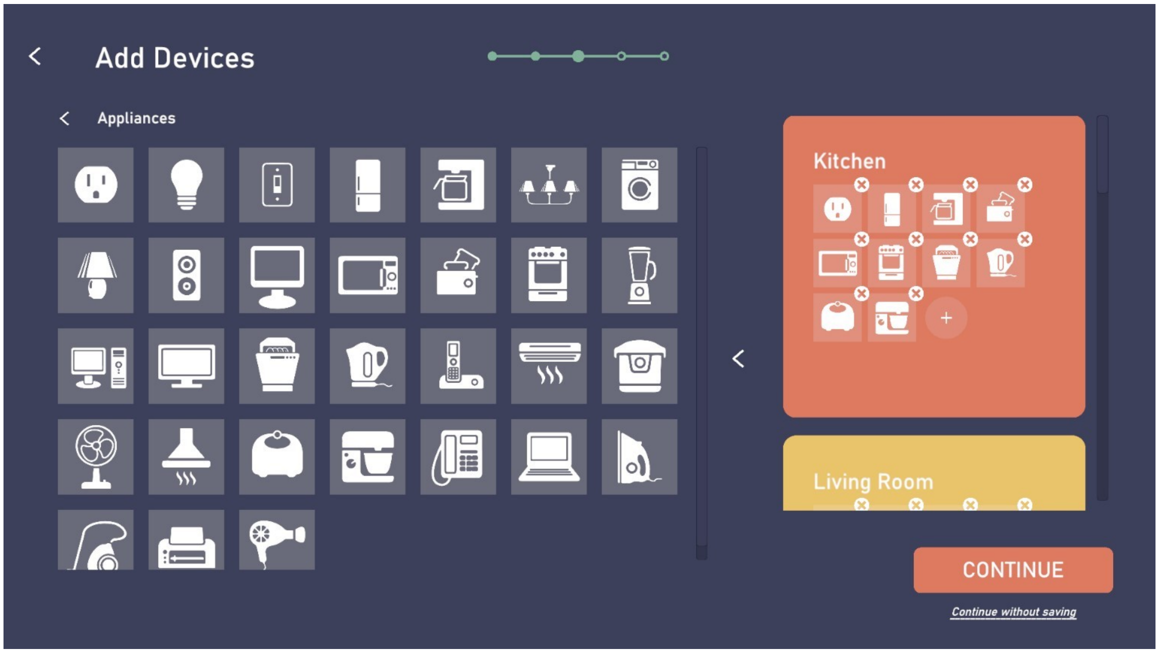




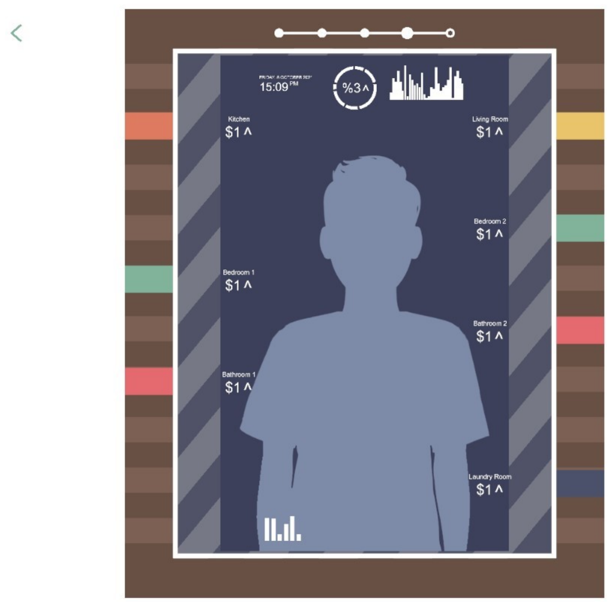

Kitchen
Bedroom 1
Bathroom 1
Living Room
Bedroom 2
Bathroom 2
Laundry Room


Add Rooms / Categories
Kitchen
Living Room
Bedroom 1
Bathroom 1
Bedroom 2
Bathroom 2
Laundry Room
CONTINUE
Continue without saving

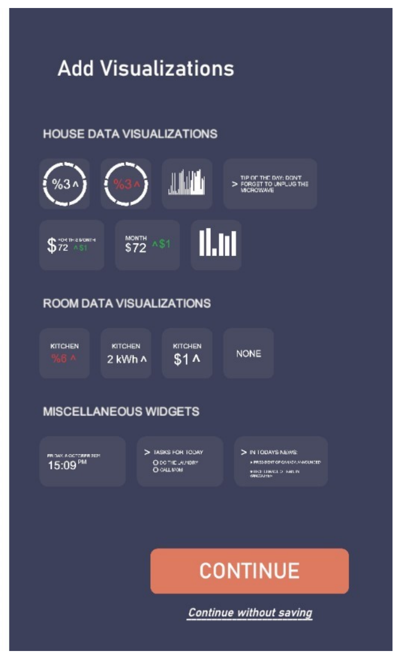

Add Devices
Kitchen
Living Room
Bedroom 1
Bathroom 1
Bedroom 2
Bathroom 2
CONTINUE
Continue without saving



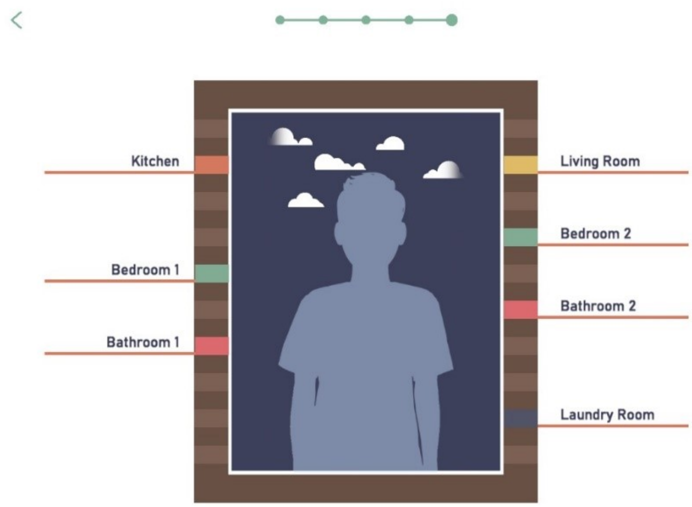
Add Devices
Appliances
Kitchen
Living Room
CONTINUE
Continue without saving

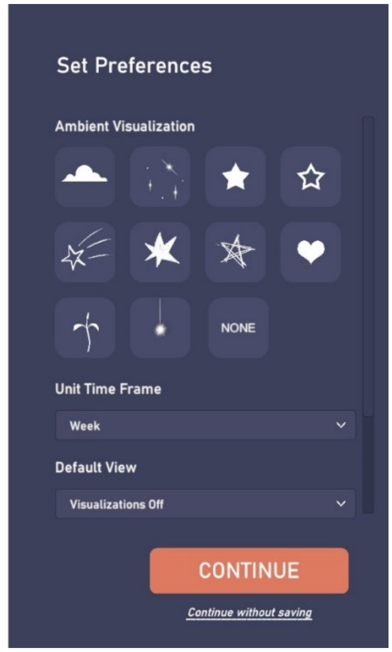


15:09
%3
Kitchen
$1
Living Room
$1
Bedroom 2
$1
Bedroom 1
$1
Bathroom 2
$1
Bathroom 1
$1
Laundry Room
$1



Add Visualizations
HOUSE DATA VISUALIZATIONS
ROOM DATA VISUALIZATIONS
KITCHEN
2 kWh
KITCHEN
$1
NONE
MISCELLANEOUS WIDGETS
15:09
CONTINUE
Continue without saving


Kitchen
Bedroom 1
Bathroom 1
Living Room
Bedroom 2
Bathroom 2
Laundry Room


Set Preferences
Ambient Visualization
NONE
Unit Time Frame
Week
Default View
Visualizations Off
CONTINUE
Continue without saving


GOOD DAY, IREM!
FRIDAY, 8 OCTOBER 2021
15:26 PM
THIS WEEK
WEEK #3
GOAL = 0 %
15
16
17
18
19
20
21
No Comparison
UPDATE GOAL
La.Ro.
Ki.
Ba.2
39%
Li.Ro.
Be.2
Be.1
Ba.1
DAILY TIPS
The following devices used more energy than usual this week!
Heater (Living Room)
Kettle (Kitchen)
LAST 30 DAYS
APPLIANCES CURRENTLY IN USE
Kitchen
Living Room


GOOD DAY, IREM!
FRIDAY, 8 OCTOBER 2021
15:27 PM
THIS WEEK
WEEK #3
GOAL = 0 %
No Comparison
LAST 30 DAYS
La.Ro.
Ki.
Li.Ro.
DAILY TIPS
The following devices used more energy than usual this week!
Heater (Living Room)
Kettle (Kitchen)
Set/Update Goal
GOAL FOR THE HOUSE
GOAL FOR EACH ROOM
%
$
kWh
kW
5
CANCEL
OK
URRENTLY IN USE
Kitchen
Living Room


GOOD DAY, IREM!
FRIDAY, 8 OCTOBER 2021
15:28 PM
THIS WEEK
WEEK #3
No Comparison
LAST 30 DAYS
Ki.
Li.Ro.
DAILY TIPS
The following devices used more energy than usual this week!
Heater (Living Room)
Kettle (Kitchen)
Set/Update Goal
GOAL FOR THE HOUSE
GOAL FOR EACH ROOM
%
$
kWh
kW
Kitchen 5
Living Room 3
Bedroom 1 0
Bathroom 1 0
Bedroom 2 0
Bathroom 2 0
Laundry Room 10
CANCEL
OK
URRENTLY IN USE
Living Room


ROOMS
Kitchen
Living Room
Bedroom 1
Bathroom 1