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An Exploration of Visual Approaches in Augmented Reality to Enhance Energy Conservation in Residential Spaces Leveraging the IoT Data

AUTHOR:

Fanjie Jin

ACCEPTED BY ADVISORY COMMITTEE:

Daragh Byrne	Principal Advisor	May 9th 2023 DATE
Daniel Rosenberg Munoz	Advisor	05/09/2023 DATE

An Exploration of Visual Approaches in Augmented Reality to Enhance Energy Conservation in Residential Spaces Leveraging the IoT Data

Fanjie Jin

Master Thesis

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College of Fine Arts
Carnegie Mellon University

Abstract

The ongoing need to increase awareness and efforts toward energy conservation in residential spaces is underscored by a pilot study investigating individuals' general attitudes toward energy conservation. The study reveals that participants (N = 12) generally exhibit a low commitment to energy conservation, indicating a need to enhance both awareness and proactive efforts in energy saving. The broader problem lies in the absence of engaging tools and interfaces that enable users to understand and manage their energy consumption in an engaging way. This could potentially be addressed through the intervention of augmented reality (AR) and the Internet of Things (IoT). However, conventional interactions with IoT devices exhibit a limited capacity to deliver rich and contextualized user experiences. To address this issue, this thesis proposes the use of AR as a critical instrument to support the understanding of energy conditions in a residential setting. AR, with its ability to merge real objects and virtual information, presents an opportunity to enhance the depth of information displayed and facilitate engaging interactions with the environment.

The research approach encompasses conducting pilot studies and leveraging the insights gained from them to consolidate the prototype direction. Through these studies, three key architectural elements are identified to promote sustainability: (1) accessibility and visibility of energy level data, (2) optimization of control mechanisms, and (3) recommendations for proactive practices. I explore both in-situ spatial mapping and the use of simulated architectural models as interaction methods to achieve the three aforementioned objectives. A speculative system in a simulated virtual reality prototype is employed to demonstrate potential applications across various scenarios. The initial attempt is presented using descriptive images to a select group of participants, followed by an analysis of preliminary findings concerning users' perceptions of the system. One preliminary finding is that both interaction methods lead to enhanced awareness of energy consumption patterns and could potentially encourage users to adopt more energy-efficient behaviors.

Keywords: Augmented reality, Spatial Mapping, Spatial Computing, Internet of Things, Sustainable Design, IoT sensors, Consumption Awareness, Energy Efficiency, Speculative prototype, Wizard of Oz

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Chapter 1
Introduction

1.1 Exploration Space

There has been a surge in interest in energy efficiency research, particularly in the residential sector[26, 30]. The increased interest stems from a growing awareness of the environmental impact of excessive energy consumption and the need to transition towards more sustainable living practices[12]. Crucially, user behavior plays a significant role in energy conservation, with substantial energy savings achievable by improving habits and heightening awareness of appliance usage patterns[1, 7, 31]. Energy visualization plays a crucial role in enabling users to access real-time household electricity consumption information, impacting efficiency and altering usage habits[1, 41, 43]. Consequently, numerous technologies and design strategies have been investigated to enhance energy efficiency in homes, promote behavioral changes, and raise awareness[5, 7]. The advent of new technology presents opportunities to enhance energy efficiency, and one of these opportunities is through the employment of the Internet of Things (IoT), which holds the promise to decrease energy utilization and contribute to sustainable development objectives [10, 22, 39].

To explore this further, I conducted interviews (N = 5) and surveys (N = 12) with experts and researchers in the field, examining various perspectives and gathering insights into the potential integration of sensors and augmented reality (AR) technology to enhance sustainability awareness and increase the visibility of energy consumption data. The study found that accessing energy information from different operational devices presents significant challenges due to the limited availability of data related to energy consumption. This lack of real-time energy consumption data for appliances and comprehensive energy bill breakdowns precludes individuals from adopting energy-saving practices.

Augmented Reality (AR) emerges as a solution to bridge the gap between user behavior and energy efficiency[10, 23, 33, 39]. AR serves as an ideal interface to facilitate visualization, as it supplies contextual information[10,

33]. While IoT functions as a channel for data communication and remote control of connected products, AR can enable data visualization, control management, and tracking of these products' activities via virtual interfaces[10, 39]. Research indicates that AR glasses may soon emerge as the preferred consumer device[20, 42, 39]. In fact, the continued advancements in computer graphics and computer vision have sparked a resurgence of interest in augmented reality as a medium for data visualization and information interaction[10, 41]. The digitally synthesized interface, overlaying physical objects, provides a tangible yet straightforward experience, making it highly accessible for displaying useful information from data sources[10,39,41]. Should AR glasses supplant smartphones in the near future, developing augmented reality interfaces for controlling Internet of Things (IoT) devices would hold substantial value [33, 42].

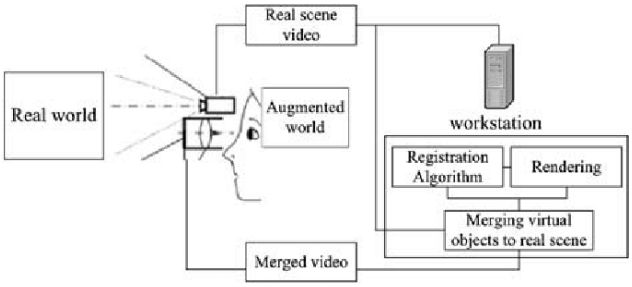


figure 1

figure 1: Architecture of AR system by Lin et al. [49]

In residential spaces, AR can significantly contribute as an IoT data visualization tool, as it allows for real-time data visualization and interaction with virtual objects, making it easier to monitor and manage devices and understands energy usage, thus enhancing user engagement and efficiency[41,10, 22]. Furthermore, AR facilitates the seamless integration of real-world objects with virtual information, producing an immersive interface for displaying comprehensive data and fostering an in-depth interaction with our surroundings[7, 39]. This interaction can be achieved through a spatially registered and visually augmented interface, such as AR glasses, which offer a direct and semi-tangible method for understanding and engaging with virtual elements[22].

1.2 Research Question

This thesis investigates the potential visual approaches integrating Augmented Reality (AR) and Internet of Things (IoT) data to enhance energy conservation in the context of residential homes. The study delves into the interaction modality between humans and AR and IoT technology, focusing on three primary sub-questions related to energy level data visibility, control mechanism optimization, and proactive practice recommendations:

1. How can we optimize the control mechanisms to adjust the parameters of appliances?

2. How can we enhance the accessibility and visibility of energy level data?

3. How can we put forth a call to actionable behavior that supports sustainable behaviors?

1.4 Contribution

As there remains a void in the literature regarding IoT's interactive potential, I fill the gap by proposing several interaction modalities for data visualization, control optimization, and recommendations in a contextually relevant way through in-situ visualization and a simulated architectural model leveraging AR. To demonstrate the feasibility and applicability of these proposed strategies, a speculative system is designed and implemented in a simulated virtual reality prototype that showcases potential applications across various scenarios. I discuss the implications of the findings.

1.5 Approach

The research process includes an examination of existing literature, along with empirical studies to gather insights into the challenges and opportunities associated with energy conservation in residential environments.

To investigate the integration of the Internet of Things (IoT) and Augmented Reality (AR), I conducted a review of the existing literature, which covered state-of-the-art research in the Internet of Things (IoT) for smart home control, energy conservation strategies using sensors, and the integration of Augmented Reality (AR) with IoT. I analyzed both well-established methods and emerging paradigms that have been proposed within the domain and contemplate their merits and limits.

Next, I conducted qualitative and quantitative studies with diverse participants to explore their views and experiences on home energy conservation. I discussed the process of consolidating the research direction through pilot studies, engaging with students, experts, and researchers in the domain of sustainable design. These conversations solidified the research direction and led to the identification of scenarios and prototyping directions.

I addressed the technical aspects necessary for achieving the integration of AR and IoT systems, laying the groundwork for the practical implementation of the proposed solution. I adopted a scenario-based prototyping approach, creating prototypes derived from the synthesized scenarios to illustrate the system's functionalities.

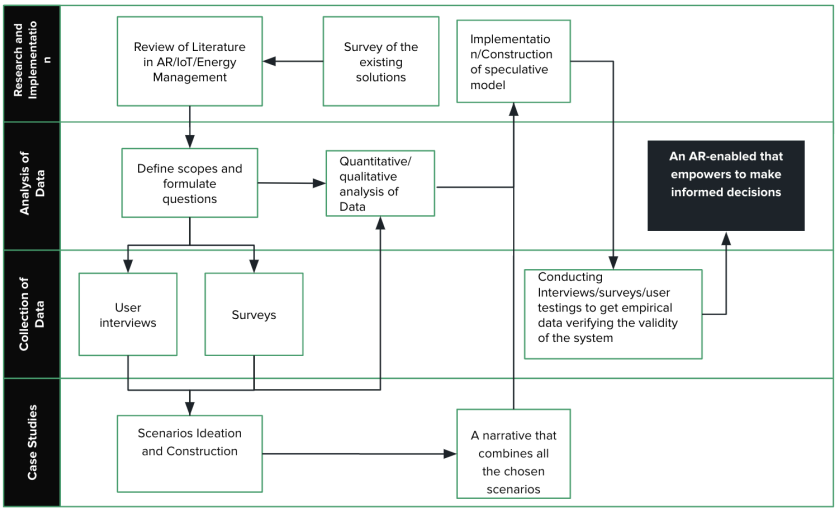


Figure 2: Methodology Diagram articulating the process I take during the different research phases.

Figure 2

Then, I conducted user testing using the prototypes to glean feedback from participants. These insights were then collected, analyzed, and synthesized. I discussed the findings and their implications at the end. Finally, I presented some preliminary findings on how potential users might perceive the system.

1.6 Organization of this thesis

The remainder of the thesis is organized as follows. Chapter 2 delves into a review of relevant studies and technical prerequisites for the IoT + AR architecture, as well as energy visualization/management in the built environment. Chapter 3 covers the two pilot studies and the scenario construction. Chapter 4 discusses the technical grounds and concepts that laid the foundation for developing the theoretical framework and presents the speculative AR-enabled prototype. Chapter 5 demonstrates the validation of the prototype. Lastly, Chapter 6 offers a summary of the study, concluding the thesis with a discussion and outlining potential avenues for future research endeavors.

Section 2
Background

Within this chapter, I analyze both well-established methods and emerging paradigms that have been proposed within the domains of the Internet of Things (IoT) and Augmented Reality (AR). I also examine the current home energy system visualization and conservation strategies, assessing their merits and limits. This investigation enabled me to gain an understanding of the existing landscape in IoT, AR, and home energy management, as well as identify areas for references and improvements.

2.1 Energy visualization and management leveraging the Internet of Things(IoT)

The Internet of Things (IoT) embodies the idea of connecting and monitoring real-world devices remotely through the Internet. These objects are embedded with sensors and communication capabilities, enabling them to exchange data with other devices and systems, allowing for extensive optimization [24]. IoT consists of sensors that facilitate data monitoring, transmission, and manipulation, allowing users to modify the properties or parameters of these devices [8]. This foundation serves as the basis for smart environments, enabling intuitive control, sharing of data across different platforms, and context-based services [7, 8, 10].

Research suggests that a significant percentage of households in the United States are actively working to reduce their energy usage at home [15]. The adoption of IoT is rapidly taking place in smart residential buildings to enhance sustainability and reduce energy consumption [7]. These sensor networks are distributed throughout the building, gathering data on aspects such as temperature, airflow, and brightness. The information can then be used to regulate the building infrastructure, enhance performance, improve occupant comfort, and reduce energy consumption. Utilizing affordable computing and cloud services, these physical objects can exchange and gather data without human input [9]. Effectively using data from IoT can assist in this endeavor, helping individuals track and monitor their energy consumption in real-time and make adjustments to reduce their energy usage. The Internet of Things (IoT) embodies the idea of connecting and

monitoring real-world devices remotely through the Internet. These objects are embedded with sensors and communication capabilities enabling them to exchange data with other devices and systems, allowing for extensive optimization[24]. IoTs consist of sensors that facilitate data monitoring, transmission, and manipulation, allowing users to modify the properties or parameters of these devices[8]. This foundation serves as the basis for smart environments, enabling intuitive control, sharing of data across different platforms, and context-based services[7, 8, 10].

Connecting objects and devices within a home to the internet allows users to remotely monitor and control them, enhancing convenience and efficiency [30, 23]. The recent advancements in information and communication technology have also led to the development of smart buildings, with occupant-centric control (OCC) being a notable example [12]. Park et al. have conducted a comprehensive analysis of field implementations of occupant-centric building controls. OCC systems gather data from occupants, indoor environments, and outdoor climates to improve occupant comfort and energy efficiency [12]. Meanwhile, Stolojescu-Crisan et al. present an open-source firmware called qToggle, a mobile-based app designed for interconnecting sensors, actuators, and other data sources for various



*figure 3: Controlling interior temperatures with qToggle app (**a**) together with smart termostats (**b**,**c**). diagram by Stolojescu-Crisan et al.[23]*

figure 3

home automation purposes [23]. The air conditioning system can be conveniently turned on and off without the need for a remote control, simply by using the toggle app. This functionality is achieved by employing a smart plug for the A/C unit as illustrated in Figure 3[23]. Fan et al. propose a smartphone app-based smart home energy visualization program that allows users to view their household electricity consumption and analyze related data intelligently. The program analyzes key power figure statistics and user behavior analysis, an optimization plan, and intelligent feedback. The app analyzes users' electricity usage habits and provides an optimal electricity usage improvement program, offering suggestions on how to use appliances more efficiently. The app also considers regional differences in power supply and prices when providing feedback and optimization plans [33].

While much research has focused on the technological aspects of IoT, there is a noticeable gap in studies examining its applicability and interaction elements [10]. Market solutions require controlling IoT devices through multiple apps, which can be confusing and complicated for users. Ideally, a single, unified solution would simplify device control. There is also a scarcity of research delving into the enhancement of IoT data visualization and manipulation in terms of usability, as well as the potential use of immersive technology for displaying data [39]. Exploring these aspects is essential for uncovering the full potential of IoT, ensuring optimal user experiences, and promoting effective integration into diverse sectors and applications.

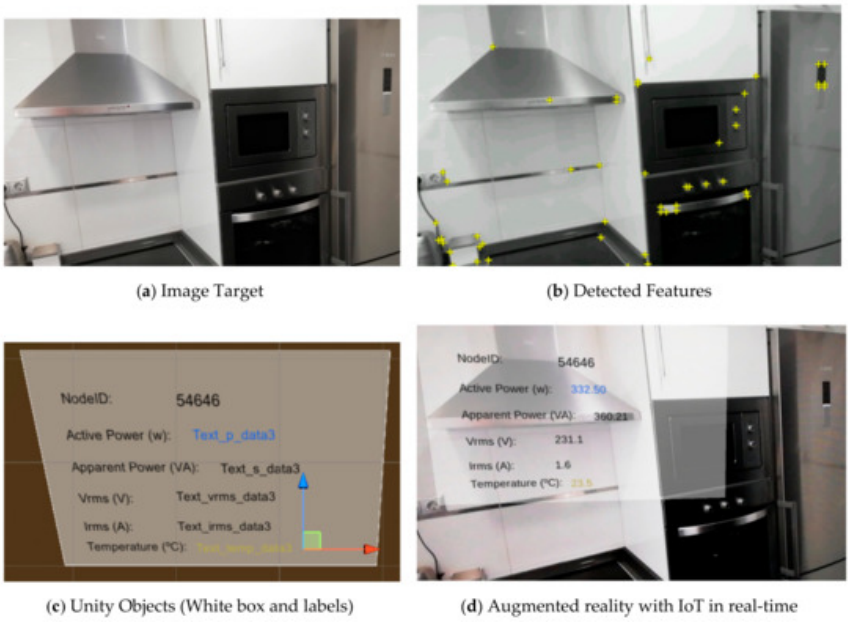


figure 4

figure 4: the energy information obtained by the IoT PQ sensor and then displayed in these virtual interfaces. Diagram by Alonso-Rosa et al.[38]

Currently, mobile apps are the primary method for operating IoT devices. This approach has its drawbacks, as users often have to switch between multiple apps to perform different actions, such as changing thermostat temperatures or controlling lights. This can create confusion and unnecessary complexity. While single-app solutions on mobile devices have been attempted, AR offers the potential for more sophisticated data visualization and input, along with displaying more in-depth information. Utilizing AR can create a more seamless and efficient experience for controlling smart home appliances and devices, potentially increasing energy-saving efficiency for the given space. The use of numerous apps for various tasks can be overwhelming and create unnecessary complexity for users [14]. Switching between different apps to perform actions can lead to confusion and a disjointed experience. A single, unified solution is often preferable to simplify device control and management. Integrating AR and IoT in a home setting can achieve this, promoting energy efficiency and reducing the need for multiple apps for device control [10]. Superimposing digital information or images onto the real world enables users to see and interact with virtual objects and monitor and manage devices to better understand and improve energy consumption [10].

2.2 AR-Enabled IoT for an Interactive Environment

AR, with its capability to superimpose digital elements into the real world, could play a role in this context. For instance, AR visualization could be used to create and show the effects of energy waste in a more tangible and immersive way, which could significantly enhance awareness and understanding of the issue among individuals, prompting them to take more proactive steps in energy conservation[10]. I then analyzed both well-established methods and emerging paradigms that have been proposed within the domains of the Internet of Things (IoT) and Augmented Reality (AR). I also examined the current state of home energy system visualization and conservation strategies, assessing their merits and limitations.

Augmented Reality (AR) complements IoT by serving as a versatile platform to visualize energy-level data and streamline device control/management processes while reducing the need for multiple apps [10, 39]. There are many advantages to combining AR and IoT. First, AR technology enables users to manipulate properties and parameters of targeted areas within their visual field, which is context-aware and allows for hands-free interaction [14]. Second, because AR can combine real-world views, offering a spatially aligned and enhanced perspective, the augmented visualization enables users to better comprehend their surroundings and the performance of various tasks [3]. The spatially integrated and visually enriched interface presents a straightforward and semi-tangible experience, making it easily understandable

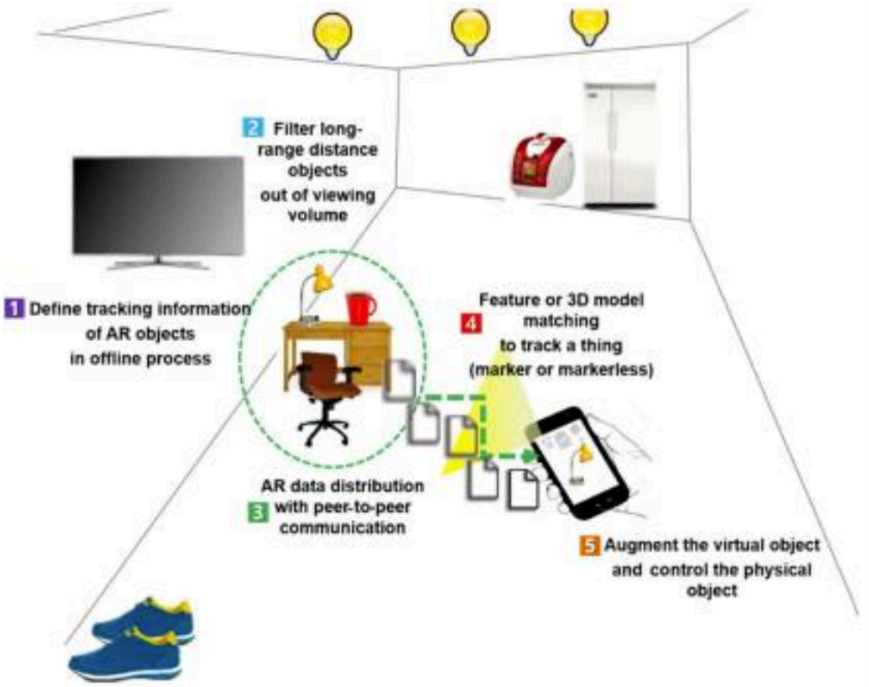


figure 5

figure 5: diagram for distributed data management scheme for "everywhere" augmented reality (AR) service for physical objects.[10]

and highly valuable, especially for daily or on-the-go use. It provides an ideal way to visualize and engage with physical objects and their related data [3]. Third, AR technology, such as smart glasses or smartphone apps, can superimpose digital information or images onto the real world, allowing users to see and interact with virtual objects while intuitively and engagingly monitoring and managing devices [14, 38, 40]. In Figure 4, Alonso-Rosa et al. presented an augmented reality-based energy monitoring system that allows users to visualize real-time power quality parameters and energy consumption of household appliances. The IoT PQ sensor is employed to glean and then deliver data on electrical parameters such as voltage, current and real power. Within this interface, individuals can simply point their smartphones at the appliance of interest to gain insight into its energy performance[38].

Academic interest is increasing in the exploration of interaction techniques that involve in-situ sensor visualization monitoring of the Internet of Things (IoT) through AR and direct object control for IoT devices. This enthusiasm has sparked potential applications for merging AR and IoT in diverse contexts, such as residential homes, commercial buildings, and urban environments [22,38]. Jo et al.'s case study offer a valuable exploration of the synergy between Augmented Reality (AR) and the Internet of Things (IoT) in the context of creating a more interactive and engaging shopping experience [10]. They have utilized a scenario-based prototyping research agenda and have explored several AR applications. As illustrated in Figure 8,

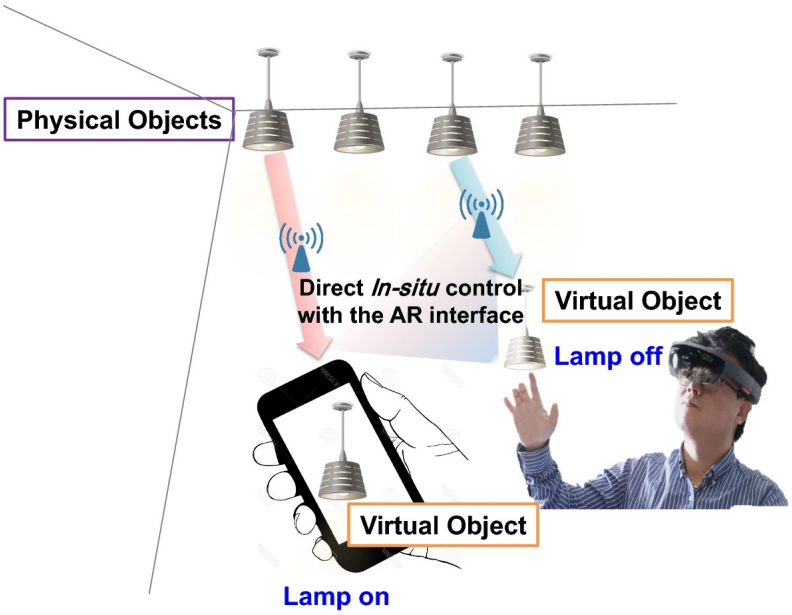


figure 6

figure 6: An interaction model using Augmented Reality to facilitate direct manipulation and examination of products for shopping.[10]

they explored utilizing a conventional mobile application equipped with AR and IoT service capabilities to locate and link to the IoT thermostat via close-range communication like Bluetooth. The app displays an AR-driven control panel, enabling the user to modify the temperature without the need to physically interact with the device or seek assistance from the front desk[39].



figure 7

figure 7: An direct interface for on-site object management, as an alternative to the conventional button interface found in Graphical User Interfaces[10]

In Figure 7, they describe a direct on-site control where AR serves as an appropriate interface supplying the essential contextual details that simplify the task and enhance understanding of the situation[10]. The authors presented a distributed and scalable information architecture that combines AR and IoT technologies, allowing for seamless on-the-spot access to IoT



figure 8

figure 8: A illustration the the scenario showing the application of object-focused data management to facilitate ubiquitous augmented reality (AR) services via the Internet of Things (IoT) network[10]

products without server limitations while providing intuitive AR-based visualization and interaction as shown in Figure 6. This architecture consists of three key components: object-centric data management and visualization, mechanisms for control, and content exchange interoperability. The researchers provided a proof-of-concept implementation for a "digital-analog" shopping experience, demonstrating its usability and satisfaction compared to

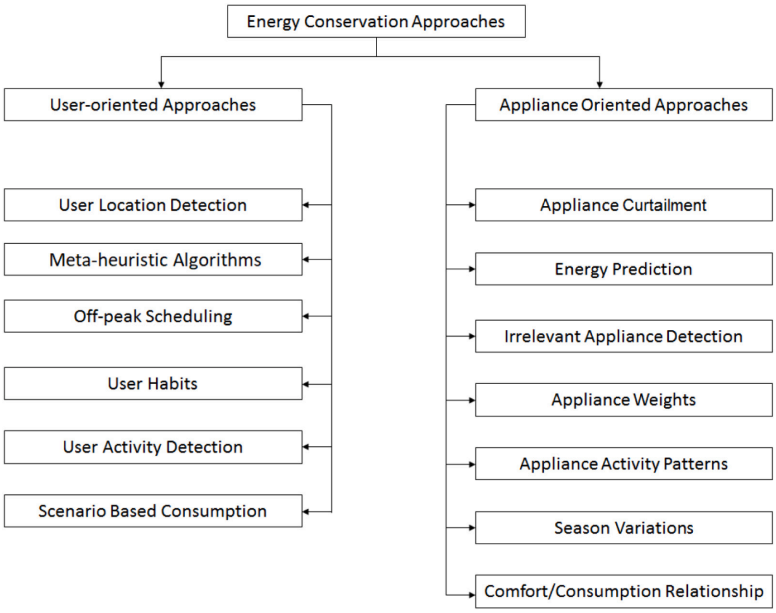


figure 8

figure 8: A Taxonomy of energy conservation approaches by [32]

conventional control interfaces. In their study, Jo et al. explored how to integrate existing AR infrastructure to enhance user interactions with physical objects in real-world shopping scenarios. The diagram is illustrated in figure 6. By combining AR and IoT, they developed a scalable and customizable interaction framework that bridges the digital and analog

worlds. Their approach leverages IoT as a control interface for physical objects and incorporates natural AR interactions to reduce latency. The pilot experiments conducted by the authors validated that users favored this integrated approach[10].

2.3 Energy Visualization and Management in the built environment

Recent research in sustainable design has identified multiple methods to reduce energy consumption and promote conservation in smart residential spaces. Fakhar et al. conducted an examination of several key aspects of energy conservation methods as illustrated in Figure 8. In the paper, they discussed the multiple energy-saving approaches, highlighting both frequently used and less common evaluation metrics, and introduce a range of methods for creating synthetic datasets related to smart home energy consumption. These approaches include modifying user habits, monitoring appliances, shifting energy load to non-peak hours, and providing energy-saving advice [30, 32]. In essence, the impact of user behavior on energy conservation is substantial; significant energy savings can be achieved by improving users' habits and raising their awareness of appliance usage patterns [31]. This can lead to both financial savings and a reduced environmental impact, contributing to the broader goal of creating more sustainable and energy-efficient communities. The advent of new technology presents new opportunities to enhance energy efficiency [10]. IoT represents one of the opportunities that offer a number of ways to enhance energy efficiency by facilitating real-time monitoring and analysis, providing energy-saving recommendations, and identifying energy wastage patterns. The concept of a globally connected network of smart devices in residential spaces has evolved from a distant idea to an emerging reality, as ubiquitous computing demonstrates the technical viability of reliably linking smart sensors for communication capabilities [10]. By revealing energy consumption patterns, users may gain an understanding of where energy is used inefficiently. Energy visualization could play a crucial role in enabling users to access real-time household electricity consumption information via various mediums to impact household electricity efficiency and alter users' electricity usage habits.

In the realm of residential energy conservation, there have been a number of investigations examining various sustainable design approaches, including device management, energy regulation, and conservation techniques. In the same paper, Fakhar et al. also discussed a theoretical foundation that they designed for identifying multiple crucial factors that contribute to achieving energy conservation. These factors include energy prediction, pinpointing irrelevant appliances, recognizing appliance activity patterns, considering seasonal variations, and examining the relationship between user comfort and energy consumption [32]. They made a classification of energy conservation

strategies showcasing the main research categories in the field of energy conservation.

An efficient smart home energy management system requires multiple components working together to achieve energy conservation[32]. Fakhar et al. made a clear diagram above summarizing the key parts. In the diagram below, they communicated how this centralized system would work. A smart automation console will serve as the key component to communicate with smart plugs connected to various devices. It controls their functionality and energy consumption and monitors energy demand. The console also communicates with smart grids and reads energy price data from providers, presenting users with energy-saving options based on appliance usage. Users can then switch off or schedule high-energy-consuming appliances to lower-price hours.

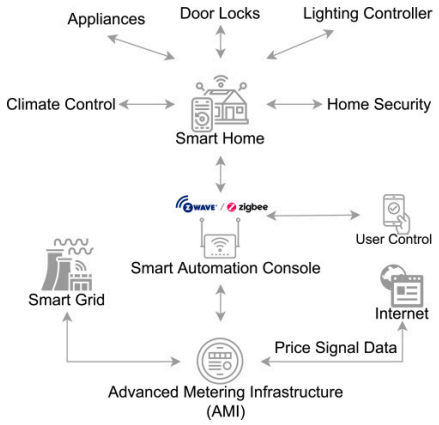


figure 9

figure 9: A diagram showing how the centralized system works highlighting the key components of an smart home management system [32]

Hopf et al. explored using energy cards, shown in figure 10, as a way to raise user awareness about energy consumption and identify potential areas for energy efficiency improvements. By visualizing data, these cards promote transparency in energy consumption[32]. Energy management, metering, and labels are organizational tools used to enhance energy efficiency[32]. The Energy Cards tool consolidates a system's energy data, facilitating a structured and transparent transfer of energy information and knowledge. Attached to systems and subsystems with color-coded frames, these cards categorize objects based on energy type and carrier, enabling comparison and easy access to energy-related data for users. Useful in both planning and operational phases, Energy Cards support increased energy efficiency and provide comprehensive energy flow tracking across all systems within a factory[32]. While primarily designed for industrial settings, the core concept can be adapted for residential applications[34].

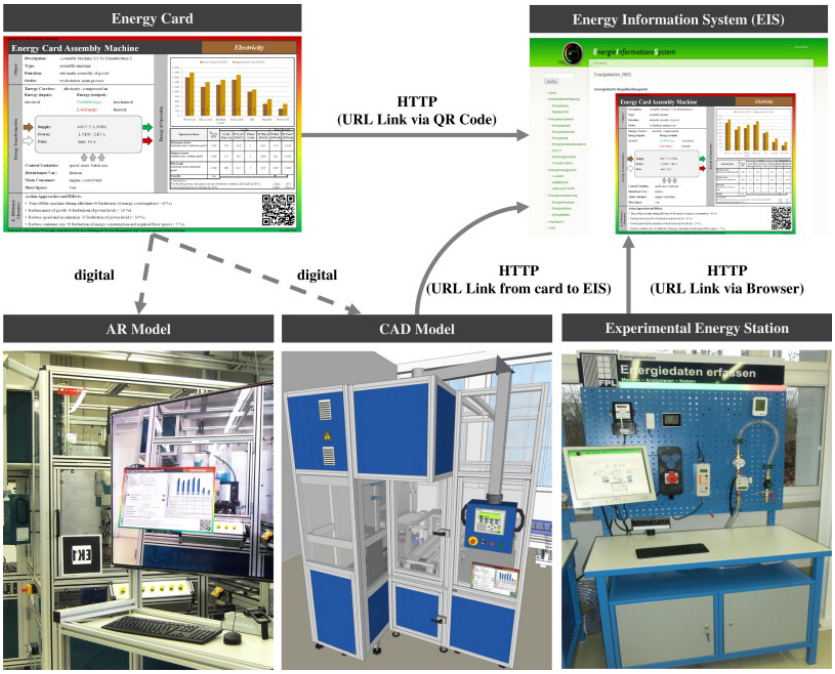


figure 10

figure 10: A diagram showing how the centralized system works highlighting the key components of an smart home management system [32]

2.4 Technical Approaches to Facilitate the IoT and Sensor Communications

In order to lay the technical ground for my thesis I explored the technical approaches to facilitate IoT and sensor communications. There are a number of wireless-based approaches to link devices. The most popular communication methods to control indoor appliances include Bluetooth, Global System for Mobile Communications (GSM), Zonal Intercommunication Global-standard (ZigBee), and Wi-Fi [26]. The reason for the different variances in the methods can be attributed to the pros and cons of different communication systems. For instance, Bluetooth-based automation offers a cost-effective, fast, and easily installed solution for short-range communication. However, it is limited by its range, which is typically about 10 meters[23, 26]. In comparison, GSM facilitates long-distance communication but necessitates a mobile plan from a local service provider. Zigbee is designed for cost-efficiency and minimal power consumption, making it ideal for battery-operated devices in wireless control and monitoring applications [26, 27]. However, in recent years, Wi-Fi technology

has been used more widely compared to all the aforementioned ones because of its increasing affordability, accessibility, expansibility, and the elimination of additional hardware purchases [26].

To control and manage sensors, microcontroller unit (MCU) boards such as Arduino and Raspberry Pi are widely used due to their open-source nature and easy expandability. Raspberry Pi is often preferred because of its greater processing power compared to Arduino. Additionally, Raspberry Pi runs a full-fledged operating system such as Raspberry Pi OS or other Linux distributions, enabling users to install various software packages, libraries, and programming languages. Notably, the ESP8266 module is a cost-effective option, ideally designed for use in Internet of Things (IoT) projects for several reasons [23]. First, it features built-in Wi-Fi support, allowing devices to easily connect to the internet or local networks. Second, the ESP8266 possesses a decent processing capability with an 80-160 MHz 32-bit processor, enabling it to handle various tasks and even run a lightweight version of Node.js. Lastly, the ESP8266 offers various power-saving modes, making it suitable for battery-powered or energy-conscious applications[23]. The optimal node and processor (controller) selection for an IoT-based home automation system depends on the user's specific requirements and desired features. Although many automation systems in existing literature utilize Arduino boards, the Raspberry Pi family is also popular due to their increased capabilities and robust computing abilities, which enable the execution of more complex software and algorithmsp[24].

qToggle utilizes a flexible yet powerful Application Programming Interface (API) to establish a simple, unified communication scheme. The majority of devices used in the qToggle system are based on ESP8266/ESP8285 chips or Raspberry Pi boards, and they implement the qToggle API [23]. qToggle facilitates the integration of different types of devices by providing a unified communication scheme through the use of JavaScript Object Notation (JSON) data format, as defined by RFC 7159. The JSON format provides a simple language for the Internet of Things (IoT). This paper also features a real-home case study showing how this app can potentially make it easier and cheaper to manage appliances at home. qToggle app features a proposed lighting control system, where users can control all the lights in the home on one single screen [23]. Similarly, Kodali et al. developed a smart wireless home security system that sends alerts to the homeowner via the internet in case of any unauthorized entry and optionally triggers an alarm. This same system can be used for home automation by employing the same set of sensors. The advantage of this system over similar existing solutions is that users can receive alerts and status updates from the Wi-Fi-connected, microcontroller-managed system on their phones, regardless of their distance or whether their mobile phones are connected to the internet[23]. The current prototype utilizes the TI-CC3200 Launchpad board as the microcontroller, which features an

embedded microcontroller and an onboard Wi-Fi shield. This setup enables users to control and manage all electrical appliances within their homes [28].

Chapter 3
Pilot Studies & Scenario Construction

In this chapter, I discuss the process of consolidating the research direction through pilot studies, engaging with students, experts, and researchers in the domain of sustainable design. These conversations solidified the research direction and led to the identification of scenarios and prototyping directions. Lastly, I discuss how the insights obtained from this study contribute to the development of various scenarios.

3.1 Pilot Studies - Surveys

3.1.1 Survey structure

For the qualitative study, the group comprised one professor specializing in sustainable building technology, along with four master's students in sustainable building performance programs. Meanwhile, for the surveys, the respondents were all bachelor and master students from Carnegie Mellon University.

I began with a survey of participants to understand their overall stance on energy conservation. The questionnaire was shared with students through channels, including Discord, WhatsApp, and WeChat groups. I also directly reached out to some participants to increase the response rate. Eventually, I recruited 12 participants. All the participants were students from Carnegie Mellon University with different backgrounds, currently residing in shared living arrangements with other housemates. The average age for the participants was 23.4, with four identifying as female and eight identifying as male. I asked the participants to evaluate their initiatives in raising awareness about energy savings to determine if this area represents a significant concern. These are the survey questions:

Q1. On a scale of 0 to 7, where 0 indicates a complete lack of interest or concern, and 7 indicates an extremely strong commitment, *what is your general attitude toward energy conservation?*

Q2. On a scale of 0 to 7, where 0 indicates that you do not actively engage in building awareness about energy saving, and 7 indicates that you have taken extensive and proactive measures to build awareness, *how would you rate your efforts in building awareness about energy saving*?

Q3. On a scale of 0 to 7, where 0 indicates a complete lack of knowledge about smart home technologies or systems that can help manage and reduce energy usage, and 7 indicates extensive knowledge and a deep understanding of these technologies or systems, *how would you rate your awareness of smart home technologies or systems that can help manage and reduce energy usage*?

Q4. On a scale of 0 to 7, where 0 indicates a complete lack of awareness of energy waste in your house, and 7 indicates a highly sophisticated and comprehensive understanding of energy waste and its causes in your house, *how would you rate your level of awareness of energy waste*?

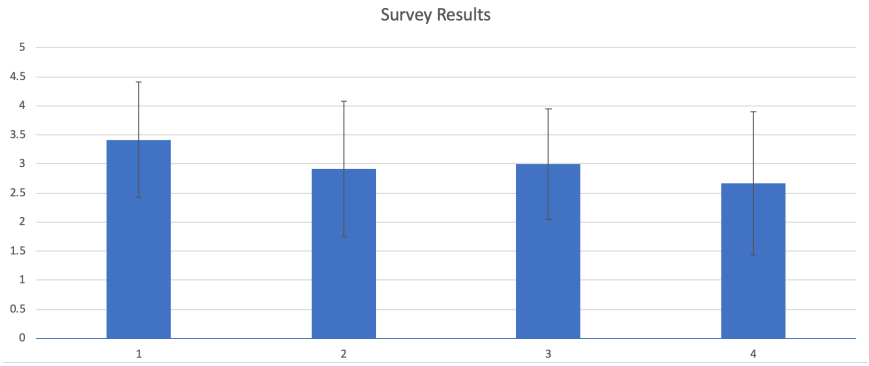


Figure 12

Figure 12: This chart depicts the calculated results from the survey, highlighting the levels of awareness regarding energy wastage and overall attitudes towards energy conservation. The X-axis denotes the individual questions, with '1' corresponding to Q1. The Y-axis, on the other hand, showcases the scores for each respective question.

3.1.2 Survey Findings

The users' general commitment to energy conservation was measured, with an average score of 3.42 out of 7 and a standard deviation of 1.00. This suggests that there's a moderate level of commitment to energy conservation among the respondents. The standard deviation, being close to 1, indicates that the responses were fairly close to the mean. When asked to rate their efforts in raising awareness about energy saving, respondents returned an

average score of 2.92 out of 7 with a standard deviation of 1.16. This score suggests that while respondents are committed to energy conservation, they might not be as proactive. The higher standard deviation indicates a wider spread of responses. When the respondents were asked about their awareness of smart home technologies or systems that could assist in managing and reducing energy usage, the average response was 3.00 out of 7.00, with a standard deviation of 0.95. This suggests a moderate level of awareness, showing that while some respondents are aware of such technologies, there is room for increasing this awareness. Lastly, the respondents' level of awareness about energy waste was gauged. The average score was the lowest among all categories at 2.67, with a standard deviation of 1.23. This suggests that respondents may not be fully aware of the extent of energy waste issues. The high standard deviation indicates a wide range of responses, showing that there is significant variability in the level of awareness about energy waste among the respondents.

In conclusion, the study reveals that participants generally exhibit a low commitment to energy conservation, indicating a need to enhance both awareness and proactive efforts in energy saving. These results also underscore the need for increased efforts in raising awareness about energy conservation.

With these sets of findings, I then decided to conduct another study involving users to investigate the opportunity for design interventions.

3.2 Pilot Studies - Interviews

After establishing that energy saving is an issue that requires research attention, I embarked on a series of interviews to explore the potential avenues through which the integration of Internet of Things (IoT) and Augmented Reality (AR) technologies could be implemented. These interviews aimed at understanding the intricacies of the problem space and identifying possible ways that AR and IoT could be harnessed to address the challenge.

3.2.1 Interviews structure

This qualitative research involved a series of semi-structured interviews (N = 5) with experts and researchers in the fields of sustainable design and building performance analysis. The group comprised one professor specializing in sustainable building technology, along with four other master's students in sustainable building performance programs. The participants consisted of one professor specializing in sustainable building technology and four master's students in sustainable building performance programs. To ensure a systematic approach, the interviews were divided into four main themes, with corresponding discussion questions for each theme:

Theme 1 *Opportunities for IoT in Residential Sustainability*: In your opinion, what are some opportunities for using IoT technologies to make residential spaces more sustainable?

Theme 2 *Limitations and Challenges in Energy Conservation:* What are some common limitations or challenges that people face in conserving energy within their homes?

Theme 3 *Barriers to Adopting Energy-Efficient Practices*: What are some barriers or constraints that might prevent individuals from adopting energy-efficient practices and technologies within their homes?

Theme 4 *Information Needs for Understanding Energy Conditions*: What types of information would be valuable and relevant for users to better understand their current energy consumption and potential energy-saving opportunities?

To comprehensively analyze the data collected, I utilized a thematic analysis approach, which is a qualitative research method designed to analyze and identify patterns or themes within the data[45]. In the process of analyzing the interview data, I started with coding the transcripts, highlighting meaningful/impactful phrases or sections related to the research questions, assigning codes to segments organizing the codes into potential themes. Then, I organized the codes into potential themes. Lastly, I synthesized the findings into a narrative, discussing the insights gained from the thematic analysis[45].

3.1.2 Interview Findings

Engaging with the participants enabled me to capture an array of viewpoints and experiences. I delved into various perspectives and gathered insights into the potential integration of sensors and augmented reality (AR) technology to promote sustainability awareness and enhance the visibility of energy consumption data. These insights ultimately guided the direction of the prototype, enabling me to concentrate on specific features and functionalities that strategically aligned with the research objectives and effectively addressed the challenges at hand.

Insight 1: T*here are several well-established Internet of Things (IoT) infrastructures that assist in energy conservation.*

Two interviewees emphasized the potential of IoT in enabling real-time monitoring and control of energy usage, optimizing system efficiency, and identifying energy-saving opportunities. This observation aligns with findings from the literature review, which confirm that there are numerous well-established IoT infrastructures that contribute to energy conservation [10, 23, 34, 39]. These IoT technologies not only enhance the comfort and

convenience of the home but also play a crucial role in effectively managing and reducing energy usage[6, 19, 33]. The discussions also prompted me to investigate the range of IoT devices available in the market that can contribute to energy conservation. Some of these devices include:

1. *Smart Power Strips*: These tools work by controlling the power flow to various devices plugged into the strip based on certain criteria. They help to minimize energy use by automatically cutting off power to devices when they aren't being used. This prevents unnecessary energy consumption from idle devices.

2. *Smart Lighting*: These IoT-enabled lighting systems conserve energy by intelligently responding to room occupancy and natural light levels. They automatically switch off lights when a room is not in use, or they adjust brightness according to the amount of natural light available, reducing the need for artificial light.

3. *Smart Thermostats*: These devices can auto-adjust the home's temperature based on your daily routines and outdoor temperatures. This helps conserve energy by preventing unnecessary heating or cooling of your home.

4. *Window Management:* IoT-enabled window shades and blinds can adjust themselves based on sunlight and ambient temperature. This allows them to help control indoor temperatures, thereby reducing reliance on heating and cooling systems.

Insight 2: *Lighting and heating are the primary sources of energy loss in residential buildings*

I learned from one participant that a significant 70% of energy usage can be traced back to the functioning of lighting and HVAC systems[3]. In a study by the U.S. Department of Energy, residential buildings account for 21% of overall energy consumption in the United States[2]. This statistic highlights that reducing energy consumption through efficient lighting and heating systems can significantly decrease the building's overall energy usage. Based on this finding, I decided to orient my prototype and specifically prioritize the design for lighting and heating saving.

Insight 3: *To comprehend energy usage in homes, it's crucial to incorporate information such as energy level comparisons, appliance-specific energy data, and energy bills.*

I learned that obtaining energy information from various operational devices is a challenging task due to the lack of accessible data related to energy consumption[19]. The absence of real-time energy consumption data for appliances and detailed energy bill breakdowns makes it difficult for

individuals to adopt energy-saving practices. Interviewees highlighted the importance of including the following elements:

1. *Energy level comparisons:* Users expressed interest in being able to compare their energy consumption levels with benchmarks, such as historical data, the average consumption of similar households, or energy-efficient standards. This information would enable users to evaluate their energy usage more effectively, identify areas of improvement, and make informed decisions about implementing energy-saving measures.

2. *Appliance-specific energy data:* Users also found value in having detailed information about the energy consumption of individual appliances within their household. This granular data would help them pinpoint high-consuming devices and assess the potential benefits of replacing or upgrading them to more energy-efficient models. Additionally, this information could encourage users to adopt more energy-conscious behaviors when using these appliances.

3. *Energy bills***:** Users indicated that having easy access to their energy bills and a clear breakdown of the costs associated with their energy consumption is crucial. This information can help users better understand how their energy usage translates into monetary expenses and identify potential opportunities to reduce costs through more efficient energy management.

These findings are instrumental to the development of the prototype which I will introduce in the next section.

Insights 4: *AR and IoT integration can potentially support three avenues: Control mechanism optimization, Visibility of energy level data, and Recommendations for proactive approaches*

To analyze the collected data, I employed the affinity diagramming method, which involves grouping raw data based on shared characteristics or themes[43]. This approach enabled me to effectively sort and categorize the information gathered during our discussions.

First, I identified all the methods and strategies that were collaboratively generated during our conversations. This entailed examining the content of our dialogue and isolating each proposed method. Next, I explored various sensors that could potentially support these strategies, aiming to align the technical capabilities of available sensors with the previously uncovered methods. I then created scenarios that were anchored in the interplay between the identified sensors and the corresponding energy-saving methods. Furthermore, I incorporated the benefits of Augmented Reality (AR) into

my considerations, contemplating potential design directions that could leverage AR's unique capabilities.

Through this organizational approach, I ultimately identified three predominant categories: (1) control mechanism optimization, (2) visibility of energy level data, and (3) recommendations for proactive approaches. I chose to focus on these aspects due to their potential for enhancement through the application of Augmented Reality. Drawing from the insights obtained from both the literature review and the user interviews and surveys, I consolidated these findings into the aforementioned three categories. These categories will be implemented through scenario-based prototypes:

1. *Control mechanism optimization*: This category refers to the process of enhancing the functionality and efficiency of Internet of Things (IoT) devices, specifically appliances such as lighting systems and thermostats. The objective is to increase accessibility, enhance understanding, improve responsiveness, and facilitate real-time adjustments to these systems.

2. *Visibility of energy level data*: This category emphasized the accessibility of the energy level data and its potential impact on user behavior. Accessibility, in this case, refers to making energy consumption data readily available and easy for users to understand. Energy level data refers to specific metrics related to the use of energy, such as electricity usage by a certain appliance, and the energy efficiency of a device. These data points are critical for users to understand their energy consumption patterns. The data under this category underscored the necessity of providing users with tangible, real-time information about energy consumption, enabling them to make informed decisions.

3. *Recommendations for proactive approaches*: This category is centered around strategies for anticipating and addressing potential issues. This focuses on suggesting various preventive measures and proactive strategies that could be employed to mitigate energy waste and enhance overall system performance.

3.4 Scenario Construction

By focusing on the potential ways to develop and introduce AR solutions to simplify enhancing home energy efficiency, it may be possible to bridge this gap. To underscore the existing issues and highlight the potential advantages of the proposed system, I explored various scenarios and synthesized them into one cohesive narrative. My primary focus was on two systems—thermal and lighting systems—as approximately 70% of the energy usage can be attributed to the operation of lighting and HVAC systems[3].

The following is a detailed illustration of a scenario I've designed to bring into focus the aforementioned elements and their corresponding solutions. This scenario exemplifies the issues identified in the survey results but also incorporates specific IoT technologies. The purpose of this envisioned scenario is to create a tangible and relatable context that demonstrates how these technologies can be potentially applied to address concerns about energy conservation and waste. These scenarios emphasized energy data visualization and control, illustrating how AR-enabled IoT systems assist users in achieving sustainability objectives while being immersive.

> *John is a student who resides in a spacious house, which he shares with three other individuals. Despite their best intentions, John and his roommates often neglect the importance of conserving energy in their shared living space. In large houses, it's all too easy to leave lights on in rooms that are not in use, leading to wasted energy. They frequently leave lights, appliances, and other electronic devices switched on for extended periods, even when not in use. This carelessness leads to significant energy wastage and high bills that are both environmentally and financially problematic for them. To reduce their collective expenses, John uses a head-mounted display (HMD) to activate the AR-enabled IoT system for learning about energy level data and controlling devices. The system features two ways to interact with the AR data: contextualized spatial mapping that directly presents information on the room's interior infrastructure, and interacting with a three-dimensional digital model anywhere in space. By obtaining insights into the environmental quality and building performance, John leverages these sets of information to learn about the trends and habits of energy usage. In addition to sensing and displaying energy level information, this system enables John to virtually manage appliances and manipulate their parameters. The AR-enabled IoT system allows him to change the parameters of the appliances directly through the HMD. Monitoring environmental parameters helps identify areas for improvement in building performance, such as adjusting heating and lighting as necessary.*

Chapter 4
Implementation of Scenarios

In this chapter, I begin by presenting a potential way to construct the data flow structure and manage distributed data for the realistic implementation of an AR and IoT system. I document a presumed technical approach, which is important to inform the design of the speculative VR experience. I then provide an overview of the VR prototype's implementation and demonstrate its functionality in a simulated VR environment. Finally, I showcased the resulting prototypes.

4.1 Envisioning the technical elements required for implementing the system

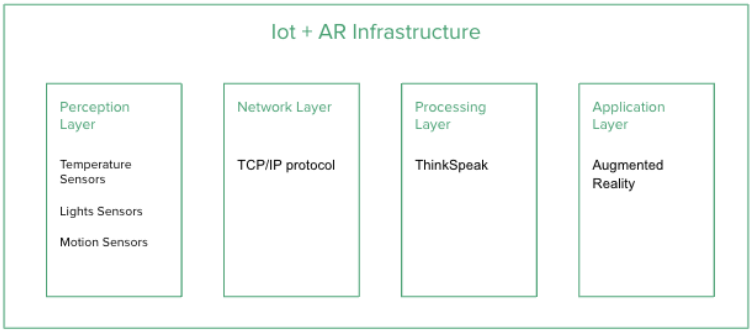


figure 13

figure 13: A diagram showcasing the four distinct layers for an envisioned technical system highlighting the individual elements that each layer contains[39]

I discussed the technical realization of an AR and IoT system through four layers: the perception layer, the network layer, the processing layer, and the application layer[35].

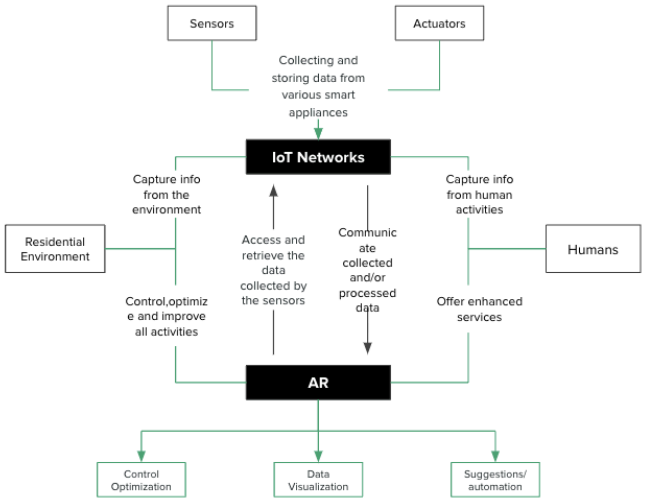


figure 14

figure 14: This diagram on the left presents the value exchange occurring between the primary components within the proposed system. Augmented Reality (AR) plays a crucial role in this exchange by enabling the seamless blending of real-world objects and virtual information. The proposed approach leverages the intuitive and natural interaction capabilities of AR, enabling users to access control interfaces and contextualized visualization methods.

4.1.1 The perception layer

The perception layer pertains to the sensors and actuators. Sensors are responsible for gathering data from the environment, such as temperature, humidity, light, and motion[8, 35]. Actuators, on the other hand, perform actions based on the data collected by the sensors, such as turning on a light or adjusting a thermostat[33]. The AR-enabled IoT paradigm relies on various sensors including temperature sensors, motion sensors, and light intensity sensors, to monitor the state of the residential environment. with sensors collecting data from the environment and actuators being triggered based on the acquired data[35].

By connecting devices and systems, IoT enables designers to create smart, and responsive systems that can adapt to changing conditions and optimize their performance[33, 35]. To regulate the HVAC system, heating, and lighting, we can rely on an array of sensors that link to the built environment to provide visibility into the data and trends to optimize resources, reduce waste, and improve efficiency. This can include everything from energy-efficient lighting and HVAC systems.

4.1.2 The Network Layer

The network layer enables internet connectivity for sensors, which is essential for the efficient operation of a home automation system. In the background chapter, I have highlighted various studies that use diverse communication technologies in the background chapter, such as wired or wireless methods, to

link sensors to nodes, or a combination of technologies to transmit data to storage centers. The residential building usually has WiFi coverage, and therefore employing the TCP/IP protocol will be sufficient to ensure seamless data transfer between the AR client and IoT devices.

4.1.3 The Processing Layer

The processing layer is used for managing, analyzing, and processing the data received from the network layer[35]. This layer incorporates data storage and computing mechanisms. The IoT cloud platform, ThingSpeak could provide an efficient method for preserving sensor-acquired information and allows access from any location in near real-time serving as the cloud platform[38]. One benefit is that it supports integration with MATLAB, allowing users to perform advanced data analysis and apply machine learning algorithms to their IoT data. ThingSpeak enables all the fundamental features of an IoT Cloud Platform, including storage, remote access, and data analysis. To facilitate the transfer of data from sensor nodes to the cloud, ThingSpeak employs channels, with each channel that can store up to eight data fields[23].

4.1.4 The Application Layer

Lastly, the application layer is the final layer in the IoT system, providing user interfaces and applications that allow users to interact with and control the IoT system. In this layer, augmented reality (AR) is used to seamlessly integrate real-world objects with virtual information, creating a simulated interface for displaying comprehensive information and enabling fully immersive interactions with our surroundings. This can be achieved through spatially registered devices, such as AR glasses, which offer a direct and semi-tangible method for understanding and engaging with virtual elements.

4.2 Implementation in Unity

With a presumed technical implementation uncovered, next, I implement the speculative system utilizing the Unity ecosystem. To implement the experiences, I used the XR Interaction toolkit and AR Foundation on Unity 2022.1.23f1. The environment is from the Unity Asset store. I leveraged a pre-existing 3D model from the Unity asset store to create a prototype to simulate the actual user experience, as shown in figure 15. This model from Unity Asset store involves a two-story house with five rooms, two bathrooms, a kitchen, a living room, a dining area, and a study.

I adopted Unity VR to simulate the residential space condition as I could simplify the process of developing the AR visualizations that necessitated accurate alignment between virtual content and actual physical objects. I chose Unity to simulate the speculative design because many parameters in



figure 15

Figure 15: Atmospheric House (Modular) by Finward Studio, https://assetstore.unity.com/packages/3d/environments/urban/atmospheric-house-modular-192712

the AR prototype were influenced by contextual factors and spatial settings, we could easily modify these elements in the VR environment to simulate the condition [18,19]. By utilizing the Unity ecosystem, I could overcome technical obstacles and hardware constraints to physically prototype IoT-AR interactions, offering a first-person perspective of the interactions. For instance, I could demonstrate changes in lighting within the VR environment when users alter inputs on a simulated interface, illustrating the effects without having to achieve this in a real-world context.

I prototyped the different visualization methods in a simulated virtual reality environment to make a simulated AR-IoT infrastructure where hand tracking and controls are integrated resembling the actual AR experiences as much as possible. By fine-tuning the interaction for each method within the virtual environment, I ensured that this simulated AR-IoT system provides an engaging user experience, bridging the gap between the simulated and the actual AR situation as much as possible.

Because the technical development of the system is not the focus, by making the simulation in Unity, I can leverage the prototypes to get quick feedback for iterations. This feedback loop contributes to more efficient refinement and improvement of the project, without the need to devote attention to the technical intricacies of the system itself.

4.3 Iterative Design Approach

During the development of AR experience, I leveraged the opportunity to share my prototypes with fellow students, and my advising committee This enable me to obtain feedback and critique of the concepts that were developed. The input greatly assisted me in refining and iterating my designs.

Incorporating the feedback I received, I have made several adjustments and improvements to the prototype. A key example of how this feedback process enhanced my design was the adjustment of the virtual interfaces within the AR experience. Initially, the virtual interfaces of the simulated model were designed to be free-floating in the space in front of the users. While this was a functional design, the feedback from peers and advisors suggested that this did not leverage the opportunity to be fully immersive. Considering the critiques, I incorporated the virtual interfaces into the physical environment within the AR space. I specifically integrated them into the furniture, making them appear more grounded and less abstract.

4.4 Resulting Prototypes

Two primary strategies were investigated to enhance user comprehension of energy conditions and facilitate some management of the building's performance:

1. *Creating a simulated architectural model for the building:* This approach involves developing a virtual model of the residential structure that mirrors its real-time performance. The simulated architectural model enables occupants to monitor, analyze and control various aspects of the building's performance, such as energy consumption, and temperature regulation.

2. *Utilizing an in-situ display:* Utilizing an in-situ display enables occupants to directly observe the building's performance in its environments providing contexts. This approach involves setting up a physical display at the building site leveraging the vacant spaces in the building, providing real-time data and visualizations of key performance parameters.

The following table outlines the chronology of the visual strategies that I will be introducing. The integration of in-situ visualization and simulated architectural models, using augmented reality, serves as a foundation for the proposed interaction modalities. These techniques enable users to engage with their surroundings in a more contextually relevant way, providing real-time feedback and actionable insights to support energy-saving practices. Additionally, one I would like to reiterate is that there lies a prerequisite assumption that the room is filled with functioning sensors including temperature sensors to detect the room temperature level, light sensors to monitor illumination, and voltage sensors to measure electrical usage from appliances.

	AR visual approach	
	simulated architectural model	In-situ Spatial Mapping
4.3.1	Visualization of Energy level data - Simulated Architectural Model	Visualization of Energy level data - In-situ Spatial Mapping
4.3.2	Control Optimization - Simulated Architectural Model	Control Optimization - In-situ Spatial Mapping
4.3.3	Recommendations for Proactive Practices - Simulated Architectural Model	Recommendations for proactive practices - In-Situ Spatial Mapping

4.3.1 Visualization of Energy Level Data- Simulated Architectural Model

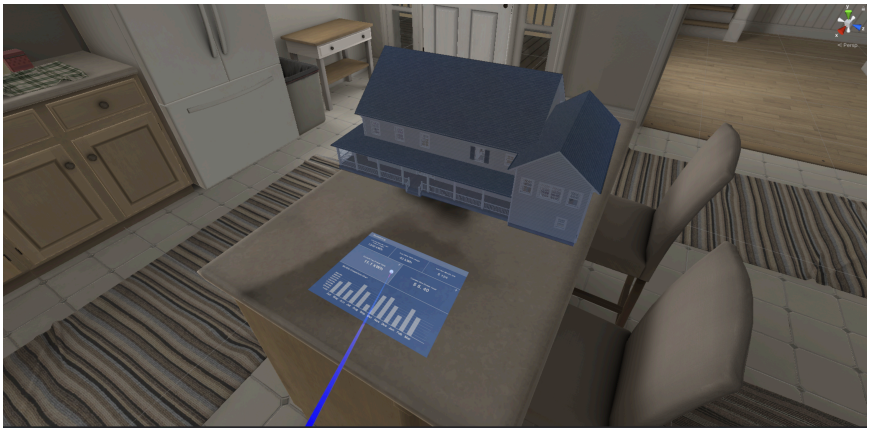


figure 15

Figure 15: The HUD augments a 3D simulated architectural model of the house on a table in the living room where the user can navigate through each room and collect information regarding information such as temperature levels, lighting conditions, energy consumption patterns, and energy cost. Each floor in the building is separately monitored.

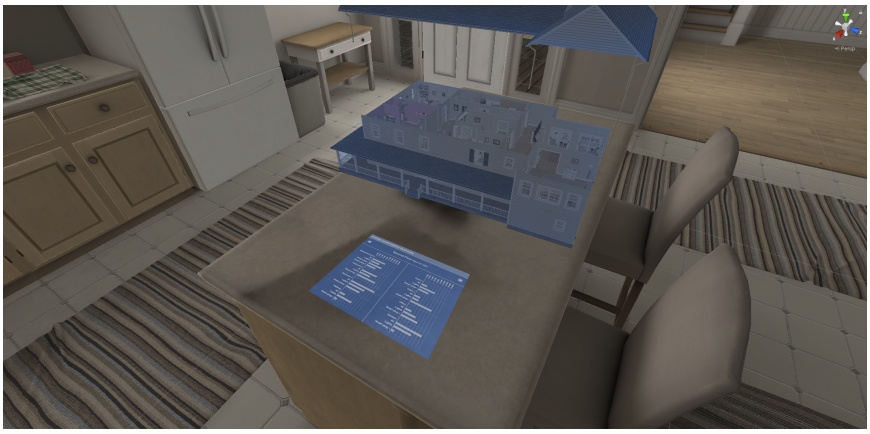


figure 16

Figure 16: Upon accessing the system, the user can select a specific floor from the model. Each floor is separately monitored ensuring individualized data collection and analysis. Once a floor is selected, the system focuses on that specific level, presenting a detailed overview of its energy consumption patterns.

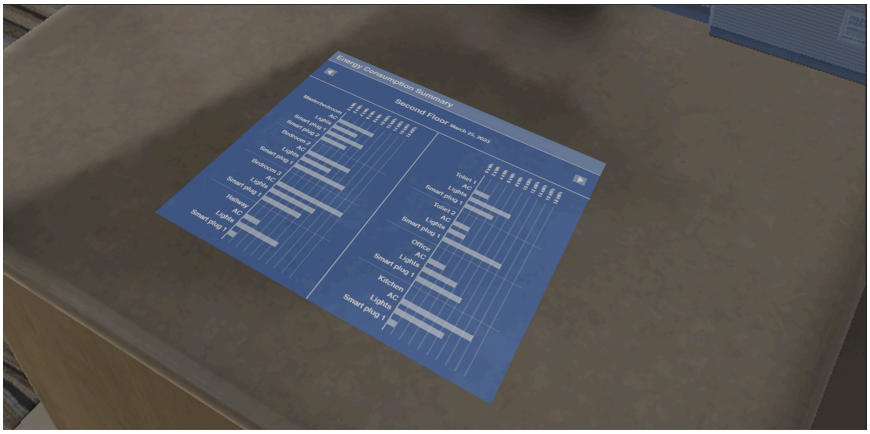


figure 17

Figure 17: When a specific floor is selected, the system unveils a holistic view of the energy consumption dynamics for that particular level. This involves a graphic visualization of the energy usage, which not only covers the broad patterns but also drills down to the granular details of individual appliances across various rooms on that floor.

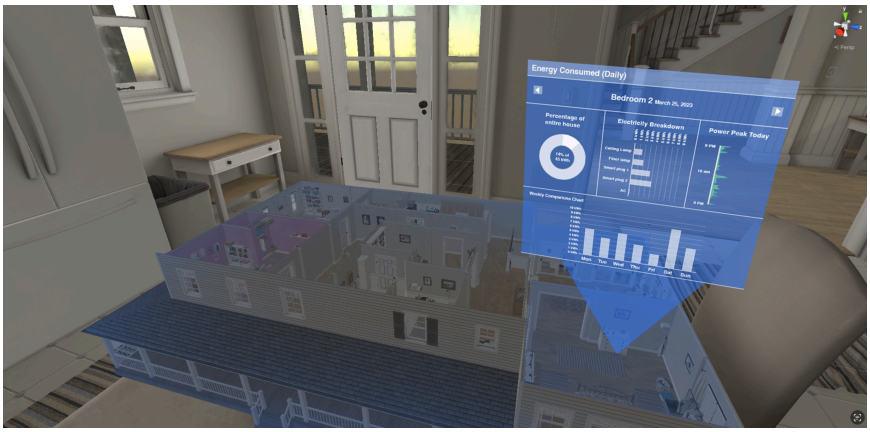


figure 18

Figure 18: Once the user selects a single room, they can see the detailed visualization that aids the user in understanding how energy is consumed at different times of the day or different days of the week, helping them identify trends, anomalies, or opportunities for energy conservation. These patterns include real-time energy usage, historical usage data, and peak consumption periods.

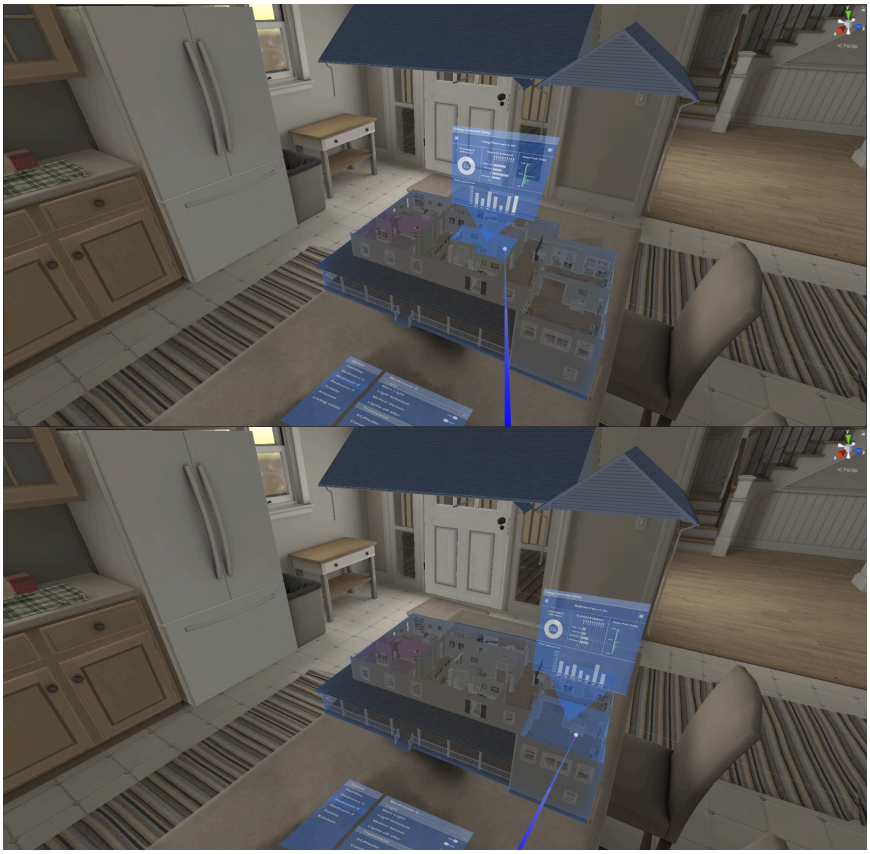


figure 19

Figure 19: The system also enables a comparative analysis across different rooms on the selected floor. This functionality is especially beneficial as it offers a broader perspective on energy consumption patterns within the building, beyond just the individual room level. Each room's energy usage is logged and displayed within the system, allowing users to easily compare energy consumption rates from one room to another. This room-to-room comparison feature can highlight disparities in energy use that may not be immediately apparent when rooms are considered in isolation. For instance, it could reveal that one room uses significantly more energy than others, even when they have similar appliances or square footage. Moreover, the comparison feature provides insight into the effectiveness of energy conservation measures. For instance, if energy-efficient lighting was installed in one room but not another, the system could show the difference in energy usage between these two rooms, thereby quantifying the impact of the energy-efficient lighting.

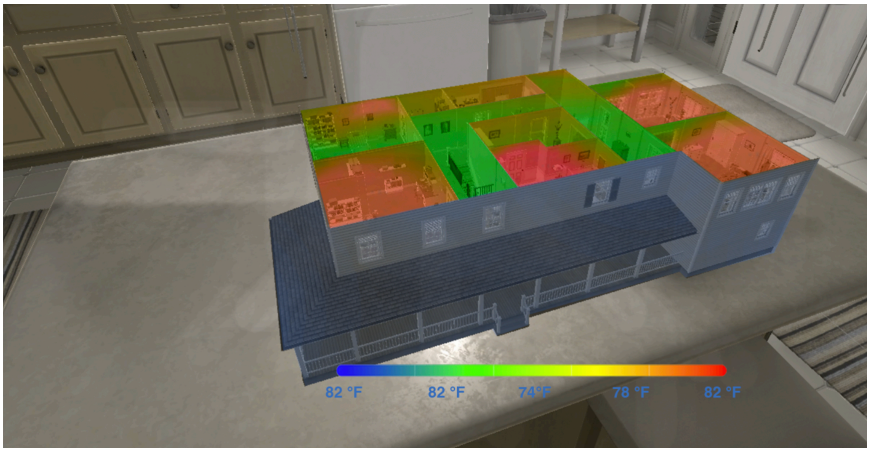


figure 20

Figure 20: This system offers a feature whereby the user can visualize the temperature across different areas of the floor through a color-coded model. In this model, different colors correspond to different temperature ranges. Cooler temperatures are represented in shades of blue, while warmer temperatures are depicted in hues of red. The user can view this color-coded temperature model for a chosen floor, with each color overlay indicating the specific temperature range in that area. This provides an immediate, visual understanding of the temperature distribution.

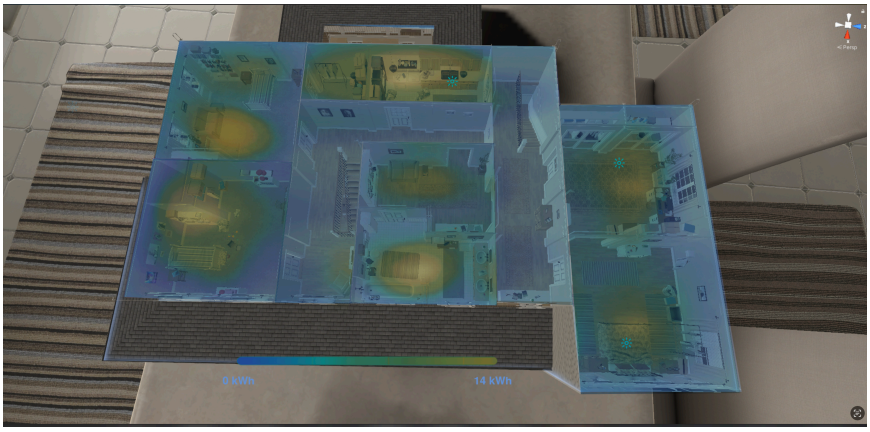


figure 21

Figure 21: The system introduces an alternative approach to visualizing energy consumption across various rooms in the building. This method employs color intensity to represent different levels of energy usage, offering a visual understanding of energy consumption patterns. In this color-coded model, varying shades of color are used to illustrate the range of energy consumption levels. The principle is straightforward: the brighter the color, the higher the energy usage in that particular area. Conversely, darker shades represent areas with lower energy usage.

Visualization of Energy Level Data - In-Situ Spatial Mapping



figure 22

Figure 22: The system includes a feature where virtual interfaces are projected onto the wall, presenting an array of valuable information in a visually engaging and interactive manner. This makes the energy consumption data more tangible and easier to understand, thereby facilitating more informed decision-making. One of the key pieces of information displayed on this virtual interface is the energy trend. It allows users to see the impact of any energy-saving measures that have been implemented. The virtual interface also provides a percentage figure that puts the energy usage of the selected room in perspective relative to the entire house. In addition, the interface includes a detailed electrical breakdown. This show how much electricity is being used by different appliances or systems within the room, such as lighting, HVAC systems, computers, and other electronic devices. This breakdown can help users understand which appliances are the most energy-intensive and might therefore be targeted for energy-saving measures.

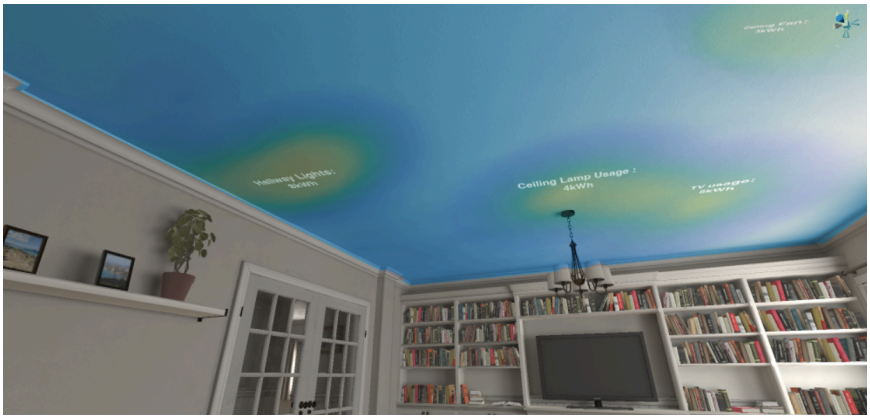


figure 24

Figure 24: The user has the ability to see real-time, energy-related data being projected onto the vacant ceiling of the room. This feature leverages underutilized space to create an immersive display that transforms how energy data is understood and interpreted. A key component of the display is the individual energy consumption data for each appliance within the room. Every device, whether it's a computer, a heating unit, or a lighting fixture, is represented within this visualization. Each appliance's energy usage is depicted, through varying shapes, colors, or sizes that correspond to the amount of energy it consumes.

4.3.2 Control Optimization - Simulated Architectural Model

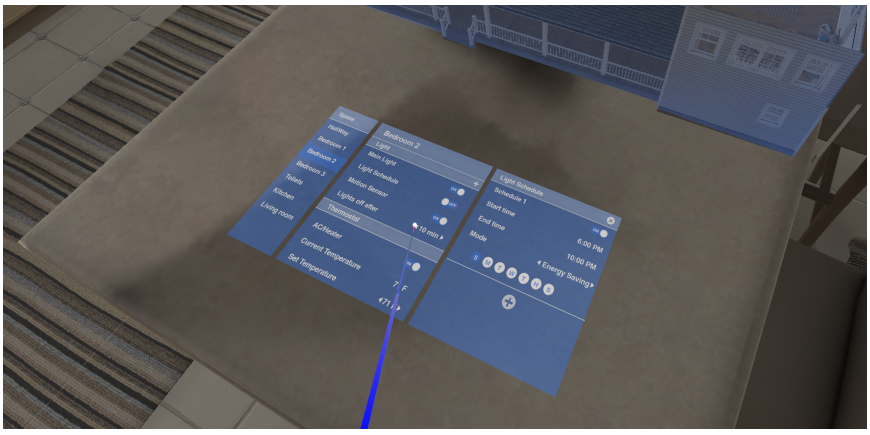


figure 25

Figure 25: The system includes virtual control panels that are conveniently located next to the simulated model of the building. These panels serve as an interface that allows the user to manipulate a range of parameters associated with the building's energy use and comfort settings. One key aspect that can

be controlled through these panels is the lighting interval when motion sensors are deployed. This refers to the duration for which lights remain on after motion has been detected. By adjusting this interval, users can ensure that lights are not left on unnecessarily when rooms are unoccupied, thereby conserving energy. The panel also provides control over the settings for the lights themselves. The heating and air conditioning (AC) systems can also be managed through the virtual control panel. This allows the user to set the desired temperature for different rooms and adjust the operating times of the heating or AC units. These controls can be used to minimize the energy use of these systems, by ensuring they are only in operation when needed and are set to an energy-efficient temperature

Control Optimization - In-Situ Spatial Mapping



figure 26



figure 27

Figure 26,27: The virtual control panels projected onto the vacant architectural space provided by the system offer a high degree of flexibility and control to the user for managing the lighting and thermal conditions in the building. This ability to adjust key parameters can lead to energy management. When it comes to lighting, the user has the capability to control various parameters.

4.3.3 Recommendations for proactive practices - simulated architectural model

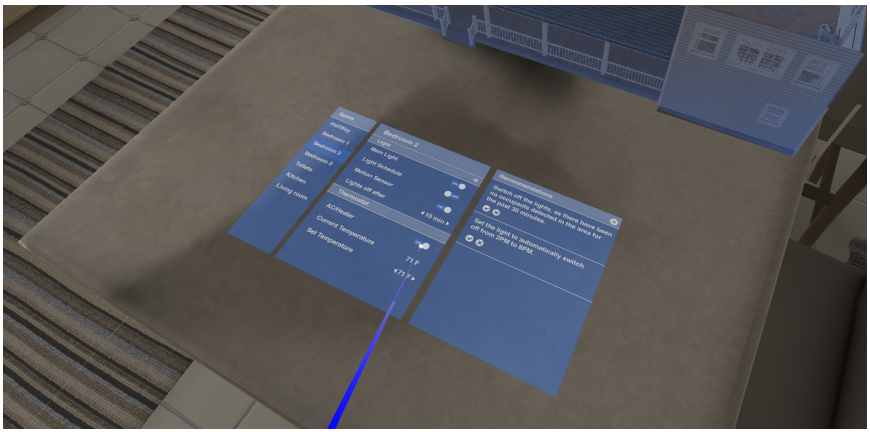


figure 28

Figure 28: Next to the control interfaces, there is a dedicated panel that provides personalized recommendations based on the current energy levels and usage patterns within the building. This panel leverages data analysis and predictive algorithms to offer advice tailored to the building's specific energy profile, thereby assisting the user in making more informed and effective decisions regarding energy management. The recommendations provided on this panel are dynamically generated based on real-time energy data. For instance, if the system detects that a particular room is consuming a significant amount of energy, it might suggest ways to reduce this consumption, such as adjusting the lighting or temperature settings or

addressing potential issues with the insulation or the HVAC system in that room. The panel could also provide recommendations based on usage patterns over time. For example, if the data shows that energy consumption tends to spike at certain times of the day or in certain seasons, the panel might suggest strategies to smooth out these peaks and achieve more consistent, efficient energy usage. Furthermore, the recommendations panel can offer advice on how to optimally implement energy-saving technologies or practices. For instance, it might suggest the best times to use energy-intensive appliances to take advantage of off-peak energy rates or recommend the installation of motion sensors in rooms that are frequently left unoccupied with the lights on. By providing these personalized, data-driven recommendations, the panel serves as a valuable resource for users seeking to optimize their energy usage. It takes the complexity out of energy management, offering clear, actionable advice that can lead to significant energy savings and more sustainable use of resources.

In-Situ Spatial Mapping - Recommendations for proactive practices



figure 29

Figure 29: This panel provides personalized recommendations, projected onto the wall. This panel offers suggestions tailored to the building's current energy levels and usage patterns, providing valuable insights for energy management. The panel's recommendations are not just general suggestions; they are specifically based on real-time energy data from the room where the panel is located. This means the advice provided is directly relevant to the space, making it highly actionable for the user. For instance, if the room is currently consuming a high amount of energy, the panel might suggest adjusting the lighting or temperature settings. It could recommend dimming the lights or changing the color temperature to a more energy-efficient setting. If the heating or air conditioning system is running at full capacity, the panel might suggest adjusting the temperature setpoint to a more efficient

level or checking the system for potential inefficiencies. In addition to real-time data, the panel also considers historical energy usage patterns for the room. For example, if the data shows that energy consumption tends to spike at certain times of the day or on certain days of the week, the panel might suggest strategies to smooth out these peaks, such as scheduling energy-intensive activities for off-peak times. The panel also offers advice on how to implement energy-saving technologies or practices within the room. It might recommend the installation of motion sensors for the lights, or suggest using energy-efficient appliances. It could also offer tips on optimizing the use of natural light and ventilation to reduce the need for artificial lighting and air conditioning.

4.5 Summary

The prototype served as a testing ground for visual approaches integrating AR and IoT data. During the preliminary pilot studies, a crucial part of the process was to identify what data would have the most substantial impact on user interaction and understanding of the AR screen. These include room-based energy visualization, which provided a tangible and immediate understanding of the energy consumption in different areas of the residence. Additionally, integrating visualizations related to energy bills provided a direct economic perspective, bridging the gap between energy usage and financial implications. The visual strategies implemented in the prototype were designed to directly address these findings.

The prototype was also designed to test methods that would enable users to control and adjust various appliances' parameters and enhance the visibility and accessibility of energy-level data. The exploration of a virtual model mirroring the real-time performance of the residential structure, and an in-situ display provided two unique avenues for engaging with the data. The use of virtual displays within the actual environment of the building, offering real-time data and visualizations, allowed occupants to receive immediate, contextually relevant feedback about their energy usage. By getting virtual displays within the actual environment of the building and providing real-time data and visualizations, occupants are given immediate, contextually relevant feedback about the building's performance.

Chapter 5
Evaluation

This chapter discusses the user testing methods and the implications of the effectiveness of the resulting prototypes. The findings from the user testing sessions are analyzed, highlighting the key insights and participants' feedback and presented.

5.1 User Testing Methods

I recruited 8 participants to facilitate the user testing to assess how the final design outcome meets the initial research question. All the participants were students from Carnegie Mellon University with different backgrounds, currently residing in shared living arrangements with other housemates. The average age for the participants is 24 with two identified as female and six identified as male. The goal of the study was to gather their insights and opinions on the proposed AR and IoT solutions for controlling energy consumption/promoting eco-friendly habits and to evaluate the effectiveness of the system.

I utilized Unity screenshots, coupled with some post-processing curation, as a means to present users with prototypes for feedback*. I chose to use images as a method of generating feedback because of two reasons. Firstly, I wanted to expedite the evaluation process. Secondly, users are generally more inclined to focus on interaction patterns when using headsets, rather than assessing the information content. Using descriptive images for feedback enabled a greater focus on the core objectives of the study.

** Initially, I attempted to employ recorded videos and Oculus headsets for idea generation during the iterative process, but this approach proved time-consuming to set up and requires extensive explanations to users.*

The user testing followed a semi-structured approach, enabling the participants to freely express their opinions while adhering to a general guideline [44].

Each interview session was scheduled as 25 minutes long and followed the steps below:

** This process had priming issue, which I will discuss in the limitation section.*

1. I spent 5 minutes using slides to provide a brief overview of the research objectives and research questions* to get them familiarized with the context of the study.

2. After giving them some context about the study, I presented with the participants six different prototype series in image format for the participants to review.

3. For each series, I initially encouraged participants to think aloud and comment on any aspects they found interesting. Following this, I asked them to address three guiding questions with respect to each prototype:

    i. *In your opinion, how effective are the control mechanisms in adjusting the controller's parameters for light and temperature regulation using the in-situ and simulated architectural model?*

    ii. *How successful do you think the accessibility and visibility of energy consumption information, as well as room energy level data, are in raising awareness about energy usage?*

    iii. *To what extent do you believe the application of insights gleaned from energy consumption data can inspire individuals to adopt environmentally-friendly energy practices?*

    iv. *What do you think about the controls in manipulating the parameter of the appliances in-situ and in the simulated architectural model?*

I concluded the session by posing an open-ended discussion question: *In your opinion, how successful is the combination of AR and IoT data in promoting sustainable energy consumption habits?*

5.2 User Testing Findings

5.2.1 Visibility of energy level data

Based on the results obtained from the study, it was observed that all participants, (a total of 8 out of 8), were in agreement that the integration could potentially contribute to increasing the awareness of the current condition concerning energy saving through in-situ spatial mapping as well as the simulated architectural model. In particular, P3 mentioned that “I believe the immersive nature of the integration could make it easy for me to grasp the importance of energy saving, as it was demonstrated through the use of in-situ spatial mapping and simulated architectural model."

Several (5 out of 8) participants noted the effectiveness of the simulated architectural model in providing a comprehensive overview of energy consumption patterns, which facilitated informed decision-making in optimizing energy usage. In particular, P2 mentioned that “I think it’s effective to visually see these breakdowns in graphical forms to see which room has used more energy especially when you are sharing spaces with somebody else.” A similar note is shared by P1 who stated that “I believe it's quite impactful to view these energy consumption breakdowns in graphic representations while being able to visually connect to the particular room”. P3 also underscored one advantage that comes with the integration, “The detailed energy breakdown is very comprehensive and I think the comparison of the energy usages in the digital model can be very useful. P4 commented that “I see this method of representing temperature as a great way to enhance the user's understanding of the thermal conditions within the building.”

A majority of the participants (5 out of 8) appraised the interactive aspect of the in-situ visualization. P1 specifically noted, “... The ability to see each appliance's energy consumption in each room, displayed directly on the wall, can significantly increase awareness regarding the energy usage pattern of that specific appliance.” “The projection of virtual interfaces on the wall provides users with a visually engaging and easy-to-understand method of accessing and interpreting energy data.”, P2 mentioned that “This breakdown can help users understand which appliances are the most energy-intensive and might therefore be targeted for energy-saving measures.” P7 noted that “I really like the utilization of the empty architectural space to show the energy pattern visualization. This is very immersive and I think it’s a great use of the AR technology”, P3 also mentioned that “I see that the visualization presented on the ceiling is not merely numeric data... it could be an engaging visual representation that adds a level of intuitiveness to the information being conveyed.” “The energy data projected on the ceiling could provide the user with a visually appealing and accessible means of understanding the room's energy consumption.”

A few participants (2 out of 8) underscored the potential of this system to cultivate a shared sense of accountability and collaboration among various occupants. P5 underscored the value of the in-situ simulation as a tool that aids in visualizing the real-time effects of energy-saving actions within their physical context, simplifying the understanding of how these actions affect overall energy consumption. Similarly, P7 noted, "This system provides potential educational advantages, as it can be leveraged to educate the significance of energy conservation and the role technology plays in fostering a sustainable lifestyle.” P4 mentioned, “the integration of IoT and AR technologies offers promising opportunities for developing novel approaches to support energy-efficient practices and drive positive behavioral changes among users.” Similarly, P1 noted that “AR technology, on the other hand,

can enhance user engagement, making the interaction with energy-saving devices and systems more immersive and intuitive.”

5.2.2 Control Optimization

Overall, the use of AR for control received less positive feedback compared to its application in energy data visualization. Based on the study results, only half of the participants (4 out of 8) agreed that integrating AR and IoT could potentially contribute to control optimization within the in-situ environment. Slightly more than half of the participants (5 out of 8) appreciated the ability to directly manipulate the heating and lighting system parameters through the simulated architectural model integration. P1 specifically stated, "I find it very valuable to access energy-saving insights and directly manipulate them in the AR environment through the simulated architectural model, as it allows for easy changes." P7 mentioned that "Being able to manipulate parameters such as temperature and lighting schedules on a model could help to track changes." P3 noted, "I think seeing the controls through AR can definitely make them more contextualized, allowing connections to room-level data.”

However, other participants expressed concerns about the applicability and effectiveness of the manipulation. P2 particularly mentioned, "I think it makes sense that you could change the parameters for a large building. However, when it comes to residential spaces, I'm not entirely convinced about its effectiveness." P4 said, "Although it's quite effective to see the energy level data on the simulated architectural model, I don’t think adding additional control adds much value."

All users (8 out of 8) believed that controlling the system using AR could increase accessibility and work in tandem with recommendations in the simulated architectural model. However, two participants mentioned that they didn't find it necessary to include that in the in-situ mapping. P2 commented, "Leveraging the empty space in the room as control is a good use of the space and technology." P6 mentioned, "It might be more useful in the simulated architectural model. But I can see that users could benefit from expanded information and easy accessibility if it is projected on the wall in the space.”

5.2.3 Recommendations for proactive approaches

The user study showcased a consensus among the participants concerning the advantages of employing both in-situ visualization and the simulated architectural model in the context of energy saving for providing recommendations. Yet, this aspect received the least amount of feedback. All

participants (8 out of 8) agree that the recommendation system works well both in the simulated architectural model and in-situ mapping and can encourage individuals to adopt more sustainable practices. Here are some notable comments made by the participants. P2 mentioned that “Being able to see how I can improve is effective but I would like to see how much I can save through these insights. If I can know how much money I can save from adopting one of the suggestions, that will be great.” P3 mentioned that “Estimation on how much I can save from adopting one of the suggestions will be great, otherwise I think it’s great. ” P6 said, "Spatially mapping this information can really make me aware of the actionable solutions available for improving energy savings.”

These comments underscore the importance of not only providing recommendations for energy-saving practices but also offering tangible, quantifiable insights. P1 and P3 commented on a direction that I can further improve which is to think about adding real-time visualization to show how users can potentially save energy/bills by adopting the recommendations. P1 noted that “The real-time visualization feature could really help me to grasp the immediate effects of my energy-saving efforts within the actual space. It simplifies the understanding of how my actions influence overall energy consumption, and as a result, I can make better-informed decisions."

5.3 Summary of Findings

Several high-level insights have emerged that highlight the aspects of combining these technologies for energy visualization along with energy controls in this prototyping attempt:

1. **Insight 1:** *AR interface offers enhanced interactivity and engagement:* The simulated architectural model and in-situ visualization feature interactive components can allow users to actively engage with the data. P7 mentioned, "The simulated architectural model and in-situ visualization's interactive components have made it easier for me to grasp the effects of various energy-saving strategies in real-time. This immersive experience has definitely improved my decision-making regarding energy conservation." A similar thought is mentioned by P3, “The interactive elements simplified my understanding of the impacts of diverse energy-saving strategies as they happen in real-time. This immersive experience can enhance my ability to make informed decisions about energy conservation.” P8 mentioned that “By receiving immediate feedback within the context of their living environment, occupants can make informed decisions, promoting sustainable energy practices in their daily lives."

2. **Insight 2:** *AR provides a context-rich platform:* P7 noted that "I really like the utilization of the empty architectural space to show the energy pattern visualization. This is very immersive and I think it's a great use of the AR technology." Similarly, P1 commented, "I believe it's quite impactful to view these energy consumption breakdowns in graphic representations while being able to visually connect to the particular room". This interaction allows them to observe the effects of various energy-saving strategies in real-time, fostering an understanding of the potential outcomes of their decisions.

3. **Insight 3:** *Real-time Visualization for Informed Energy Decisions is one design opportunity:* These speculative systems serve as enablers for visualizing the immediate impact of energy-saving measures within the spatial context. P5 mentioned, "The real-time visualization feature could really help me to grasp the immediate effects of my energy-saving efforts within the actual space. It simplifies the understanding of how my actions influence overall energy consumption, and as a result, I can make better-informed decisions." This visualization capability facilitates a more straightforward comprehension of the consequences of users' actions on overall energy consumption, leading to more informed decision-making. P3 also mentioned that "being able to see the direct impact of energy-saving measures in the context of the space itself will be valuable. It provides a clear picture of the outcomes of our actions. In this way, we can potentially seek to transform abstract energy data into tangible and actionable insights"

Chapter 6
Conclusions, Limitations, and Future Work

In this section, I discuss the limitations highlighting recommendations for future inquiry, future works, and conclusion.

6.1 Limitations

6.1.1 Scenario-based prototyping approach

I leveraged a scenario-based prototyping approach in the design and testing of experiences. This involves creating scenarios that represent how users might interact with a system, followed by the development of prototypes that align with these scenarios. While this approach enabled me to expedite the prototyping time allowing me to get quick feedback for iterations, there are two major limitations with the approach: 1) These scenarios do not account for every possible way a user could interact with a system 2) The designs are based on assumptions about user behavior. I will elaborate more on the specific limitations in the next section.

6.1.2 The realness of the data

Another major limitation is that the data used are assumed and not derived from real-world sources. To address this issue, it would be beneficial to utilize actual sensors installed in a residential setting to gather data for the user study. By incorporating real-time data from a home environment, the study could provide more grounded insights into the effectiveness of the AR and IoT integration and offer participants a more authentic experience, ultimately leading to more reliable results and practical applications.

The system is speculative, assuming an environment without technical obstacles to enable seamless integration. The prototype has a prerequisite assumption which is that the room must be equipped with functioning sensors, including temperature sensors to detect the room temperature level, light sensors to monitor illumination, and voltage sensors to measure electrical usage. However, its feasibility and effectiveness can only be

determined after undergoing practical testing and evaluation. The system's overall functionality is based on the assumption that each room within the facility has been installed with fully functioning sensors. As a result, the overall effectiveness and efficiency of the system are contingent upon the presence and proper functioning of these sensors in every room. In reality, determining the data flow and data distribution can present numerous obstacles, and these factors were not taken into account in this thesis.

6.1.3 Limitations of the Prototype

My original plan was to employ virtual reality (VR) headsets as a part of the user testing phase. However, as the project progressed, I encountered a significant constraint: time. The use of VR for testing, while providing extensive insights, can be time-consuming. The setup of VR equipment, troubleshooting technical issues, and the actual time taken by the users to interact with the prototype in a VR environment can all extend the testing phase duration. In response to this, I had to adapt my testing strategy to suit the project timeline, which leads to opting for a quicker method - descriptive images. Although this approach might not offer the same level of immersion as VR, it still serves the purpose of conveying the essential features and workings of the prototype. However, the trade-off is a less rich user experience, which might not capture all potential issues a user could encounter in a full VR environment.

6.1.4 Limitations of the Studies

The participants in this study are local university students who have a strong understanding of the technology involved. As a result of their familiarity, they may have a bias toward the technologically-forward approach. This is because their level of expertise and comfort with the technology might not accurately represent the general population, who may have varying levels of technological proficiency. Additionally, as university students their incentives and interest in managing home energy data may be different from homeowners. The results derived from this group may not be entirely applicable to a broader audience or accurately depict the real-world effectiveness of this integration.

Within the introduction, it should be noted that I did introduce the participants to the research questions of this thesis during the introduction section prior to the user testing. This could have resulted in a priming issue. This priming issue may lead to some bias in participant data and the responses may not reflect the participants' true reactions but rather their perceived expectations based on the primed research question. If I were to repeat the evaluation, I will not let the users know about the research question or the expected outcomes, to reduce the chance of influence and bias.

6.2 Future Work

There's an opportunity to delve deeper into the different visual approaches and visualization methods. For example, experimenting with different layouts and visualization methods can lead to the discovery of more engaging and visually appealing approaches to presenting information. This could involve exploring various visual elements, such as colors, shapes, and animation styles, as well as considering how the user interacts with these elements through different hand gestures. Additional research could also focus on detailed interaction mechanisms and the design of screens for each virtual interface. By focusing on these aspects, the prototype can offer a more captivating and informative experience for users.

Furthermore, the current research focused on in-situ and simulated architectural models as AR methods to support IoT. However, there can be more novel and bold attempts to explore the AR and IoT integration. For example, multi-layered AR visualizations could display a plethora amount of information concurrently. Assistive avatars or personal robots might support data visualization and retrieval. Additionally, voice-activated interactions, facilitated by incorporating voice recognition technology, would enable users to interact with data using voice commands, streamlining navigation, adjustments, and information retrieval.

On the other hand, another possible direction is to expand upon the current scope and explore the opportunity to build upon current IoT solutions for other purposes following a similar investigation methodology. Beyond adjusting the thermostat and controlling the lights, there's an opportunity to investigate how the synergistic integration of AR and IoT can be applied in other fields. Possible site for inquiry includes commercial buildings, public spaces, and industrial facilities. Such research could lead to innovative solutions across a wide range of industries, including smart cities, transportation.

6.3 Conclusions

The initial pilot study highlights the need for enhanced energy conservation awareness and action in homes. It shows that participants (N=12) lack the commitment to energy saving, pointing to a broader issue: the lack of engaging tools to help users comprehend and control their energy use. The pilot studies suggest that they are several data, and methods that could significantly influence users' understanding of energy conditions. For example, it's important to include room-specific energy consumption

information and energy bill data, linking energy usage with its financial consequences. By juxtaposing energy usage in different rooms, disparities became evident, underscoring potential areas for improvement. Additionally, the studies revealed the crucial need to incorporate control optimization and proactive practice recommendations into the system.

Leveraging a scenario-based prototyping approach, I leveraged descriptive images to test the visual approaches that combine AR and IoT data. In summary, feedback from participants in our preliminary user study indicates that both in-situ visualization and the simulated architectural model leveraging AR could be useful in increasing the visibility and accessibility of energy-level data, and have the potential to enhance understanding of energy-saving practices. The work conducted thus far has laid the groundwork for future exploration. However, it is important to note that while this methodology offers an expedited prototyping process and feedback loops, it also presented certain limitations. Future studies can potentially aim to incorporate real-time data from actual residential environments to generate more contextualized and grounded insights. As for future work, there is an opportunity to explore different visual approaches, various visual elements, and visualization methods to enrich the interaction with the IoT data.

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