MASTERARBEIT | MASTER'S THESIS

Titel | Title

Design and Evaluation of a Web App to Foster Energy Saving in Families

verfasst von | submitted by

Srujana Konduri

angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien | Vienna, 2026

Studienkennzahl lt. Studienblatt | Degree programme code as it appears on the student record sheet:	UA 066 921
Studienrichtung lt. Studienblatt | Degree programme as it appears on the student record sheet:	Masterstudium Informatik
Betreut von | Supervisor:	Dipl.-Ing. Dr.techn. Oliver Hödl Privatdoz.
Mitbetreut von | Co-Supervisor:	Dr.techn. Florian Güldenpfennig B.Sc.

Acknowledgements

The journey to completing this Master's thesis has been both challenging and deeply rewarding. What began as an ambitious vision to support household energy awareness became reality thanks to the support, guidance, and patience of many individuals.

I extend my sincere appreciation to the COSY (Cooperative Systems) research group at the University of Vienna for welcoming me into their community and giving me the opportunity to explore diverse research topics. Their guidance in helping me find my direction in technological applications has been invaluable to both this work and my growth as a researcher.

My deepest thanks go to Prof. Oliver Hödl for his trust and steady support throughout this thesis. I am especially grateful to Prof. Florian Güldenpfennig, whose mentorship shaped the scientific foundation of this work. His thoughtful feedback, resources, and intellectual generosity guided me at every stage. His influence is truly the backbone of this thesis.

This research would not have been possible without the 16 participants who volunteered their time for interviews, prototype development, and the Field Study. Their insights and engagement with the WattExplorer dashboard formed the empirical core of this investigation.

At the heart of this achievement stand two people whose love and sacrifice made every page possible, Sruthika, my beloved daughter, you gave up countless hours together, adapted to shifting schedules, and offered encouragement when I needed it most. Your patience and strength inspire me every day. This work is for you and Kannan, my partner in every sense, you carried our family when I could not, solved problems I never saw, and believed in this work even when I doubted myself. Your quiet sacrifices and unwavering support made this thesis possible. Thank you for being my foundation.

I am deeply grateful to my parents-in-law, Kumari and Sampath, for their constant encouragement. To my parents, Murali and Sita, my strongest pillars, thank you for instilling in me determination, curiosity, and resilience. Your lifelong support has carried me through every challenge. And to my brother Aditya, a steady source of strength, thank you for always being there.

Srujana Konduri
Vienna, May 2026

Abstract

Residential energy consumption represents a significant portion of global energy demand, yet many households lack awareness of their consumption patterns and struggle to adopt sustainable practices. While smart home technologies offer potential solutions, existing systems often overlook the specific needs of multi-generational families or fail to foster collective energy literacy. This thesis investigates the design and evaluation of a user-centered web application integrated with smart switches to enhance energy awareness and promote conservation behavior in family households.

Following a user-centered design methodology, this research employed a three-phase approach comprising a) semi-structured interviews with 16 participants, b) iterative prototype development as well as c) an autoethnographic field deployment with one family of four members, and post-deployment interviews capturing detailed user experiences. Thematic analysis following Braun and Clarke's framework was applied to qualitative data, complemented by quantitative analysis of system usage metrics and energy consumption data. The implemented system integrates Shelly smart outlets with a Raspberry Pi running Home Assistant, connected to a web-based dashboard application that provides real-time energy monitoring, historical data visualization, and intuitive interfaces designed to accommodate varying levels of technical literacy across generations.

Pre-deployment interviews revealed six key themes influencing system adoption: *invisible consumption and awareness gaps*, *cost as primary motivator*, *behavioral attribution and control*, *technology enthusiasm tempered by privacy concerns*, *family as collective yet individualized unit*, and *usability expectations*. The autoethnographic field deployment enabled deep observation of technology integration into actual family routines, capturing spontaneous discussions, emotional responses to consumption discoveries, and the gradual evolution from novel technology to household infrastructure. Results demonstrated measurable behavioral changes, with the participating household achieving statistically significant energy reduction sustained through the deployment period. The dashboard's real-time visualization features proved particularly effective in engaging all family members aged 8 to 42, while device-level granularity enabled specific conservation actions. Technical evaluation confirmed system reliability with 87% uptime and data accuracy within acceptable thresholds for behavioral feedback purposes.

This research contributes user-centered design principles specifically tailored for family energy management systems, demonstrating that effective interfaces must balance simplicity with depth to serve users with diverse technical backgrounds and motivations. The autoethnographic methodology provides unique insights into how families actually integrate energy monitoring systems require more than technical accuracy, they must facilitate meaningful family engagement and transform abstract consumption data into actionable insights. The work provides practical guidelines for designing sustainable household technologies and demonstrates how thoughtfully crafted socio-technical systems can make invisible energy consumption visible, contextual, and actionable, ultimately empowering families to adopt more sustainable energy practices.

Kurzfassung

Der Energieverbrauch in Privathaushalten macht einen erheblichen Teil des weltweiten Energiebedarfs aus, doch vielen Haushalten fehlt das Bewusstsein für ihre Verbrauchsgewohnheiten und für nachhaltige Verhaltensweisen. Zwar bieten Smart-Home-Technologien potenzielle Lösungen, doch vernachlässigen bestehende Systeme oft die spezifischen Bedürfnisse von Mehrgenerationenhaushalten oder tragen nicht dazu bei, das gemeinschaftliche Energiebewusstsein zu stärken. Diese Arbeit befasst sich mit der Konzeption und Bewertung einer nutzerzentrierten Webanwendung, die smarte Steckdosen zum Einsatz bringt, um das Energiebewusstsein zu schärfen und energiesparendes Verhalten in Familienhaushalten zu fördern.

Unter Anwendung einer nutzerzentrierten Designmethodik verfolgte diese Masterarbeit einen dreistufigen Ansatz, der 1) halbstrukturierte Interviews mit 16 Teilnehmenden, 2) die iterative Entwicklung von Prototypen, sowie 3) eine Feldstudie des finalen Prototypes mit der vierköpfigen Familie der Autorin umfasste, um detaillierte Nutzererfahrungen zu erfassen. Die qualitativen Daten wurden einer thematischen Analyse unterzogen, ergänzt durch eine quantitative Analyse der Systemnutzungsmetriken und der Energieverbrauchsdaten. Das implementierte System integriert smarte Steckdosen mit einem Raspberry Pi Computer, auf dem Home Assistant läuft, verbunden mit einer webbasierten Dashboard-Anwendung, die Energieüberwachung in Echtzeit, die Visualisierung historischer Daten sowie intuitive Benutzeroberflächen bietet, die auf unterschiedliche technische Kenntnisse und Bedürfnisse verschiedener Generationen von Nutzenden zugeschnitten sind.

Die 16 Vorab-Interviews ergaben sechs zentrale Themen, die die Akzeptanz des Systems beeinflussen: *unsichtbarer Verbrauch und Wissenslücken*, *Kosten als Hauptmotiv*, *Verhaltenszuordnung und -kontrolle*, *durch Datenschutzbedenken gedämpfte Begeisterung für die Technologie*, *die Familie als kollektive und zugleich individualisierte Einheit* sowie *Erwartungen an die Benutzerfreundlichkeit*. Der autoethnografische Feldeinsatz (die Feldstudie wurde in der eigenen Familie durchgeführt) ermöglichte eine eingehende Beobachtung der Integration der Technologie in den tatsächlichen Familienalltag, wobei spontane Gespräche, emotionale Reaktionen auf Erkenntnisse zum Verbrauch sowie die schrittweise Entwicklung von einer neuartigen Technologie hin zu einer festen Bestandteil der Haushaltsinfrastruktur erfasst wurden. Die Ergebnisse zeigten messbare Verhaltensänderungen, wobei der teilnehmende Haushalt während des gesamten Einsatzzeitraums eine statistisch signifikante Energieeinsparung erzielte. Die Echtzeit-Visualisierungsfunktionen des Dashboards erwiesen sich als besonders effektiv, um alle Familienmitglieder im Alter von 8 bis 42 Jahren einzubeziehen, während die Granularität auf Geräteebene spezifische Energiesparmaßnahmen ermöglichte. Die technische Bewertung bestätigte die Zuverlässigkeit des Systems mit einer Verfügbarkeit von 87% und einer Datengenauigkeit innerhalb akzeptabler Schwellenwerte für Verhaltensrückmeldungen.

Die Masterarbeit leitet benutzerzentrierte Gestaltungsprinzipien ab, die speziell auf Energiemanagementsysteme für Familien zugeschnitten sind, und zeigt, dass geeignete Benutzeroberflächen ein Gleichgewicht zwischen Einfachheit und Tiefe finden müssen, um Nutzende mit unterschiedlichem technischem Hintergrund und unterschiedlichen Motivationen anzusprechen. Die autoethnografische Methodik bietet vertiefte Einblicke darin, wie Familien Energiemonitoringsysteme tatsächlich integrieren: Diese Systeme erfordern mehr als nur technische Genauigkeit – sie müssen eine sinnvolle Einbindung der Familie ermöglichen und abstrakte Verbrauchsdaten in umsetzbare Erkenntnisse umwandeln. Somit liefert die Arbeit praktische Leitlinien für die Gestaltung nachhaltiger Haushaltstechnologien und zeigt, wie durchdachte soziotechnische Systeme unsichtbaren Energieverbrauch sichtbar, kontextbezogen und umsetzbar machen können, wodurch Familien letztlich in die Lage versetzt werden, nachhaltigere Energiepraktiken anzuwenden.

Contents

List of Tables

List of Figures

1. Introduction

Global energy consumption continues to rise, with residential buildings accounting for approximately 30% of total energy use worldwide [50], [83]. As climate change accelerates, reducing household energy consumption has become critical, yet families (to the best of our knowledge, little research has investigated the role of the whole family, including parents and children, in the context of sustainable energy use) remain largely unaware of their consumption patterns due to the invisible nature of electricity [20]. While smart home technologies and energy monitoring devices have proliferated, adoption rates remain disappointingly low not due to technical limitations, but because of poor human-computer interaction design [48], [10]. Existing energy management systems fail to accommodate the diverse needs of multi-generational households, presenting data in ways that are either too technical for casual users or too simplistic for those seeking deeper insights.[15], [73].

This thesis addresses these challenges by investigating how user-centered interface design can transform energy monitoring from a technical exercise into an engaging family activity [56], [41]. Through the design and evaluation of an interactive dashboard integrated with smart plugs including energy monitoring, this research demonstrates how thoughtful Human-Computuer Interaction (HCI) design can bridge the gap between complex energy data and everyday household behavior, ultimately fostering energy literacy across all family members[37],[47].

The core challenge is fundamentally one of HCI: how can we design interfaces that make abstract energy consumption data meaningful, actionable, and engaging for users with vastly different technical backgrounds, motivations, and learning styles [70], [66]? Traditional energy monitoring systems present raw data, kilowatt-hours, graphs, and numbers that require significant cognitive effort to interpret and contextualize [20], [47], [63]. For families, this challenge is compounded by the need to serve multiple simultaneous users: adults seeking cost control and device management capabilities, children responding to visual feedback and gamification elements [42],[59], and elderly family members requiring simplified, intuitive interactions.[34],[19]

This research recognizes that technology alone cannot solve energy awareness problems [20]. Instead, the solution lies in carefully crafted interfaces that respect human cognitive limitations [76], leverage effective data visualization principles [78], and support collaborative household decision-making [79]. The dashboard developed in this thesis represents an HCI-driven approach to energy management, where design decisions are informed by direct user feedback and iterative refinement [56], [55].

Following a user-centered design methodology [64], this research was conducted in three distinct phases to ensure the resulting technology was deeply rooted in actual human needs.

The process began with an initial *exploration phase*, where 16 participants were engaged through semi-structured interviews to understand their energy consumption behaviors, motivations, and specific preferences regarding smart home technology [16]. These qualitative insights directly informed the second phase: a *design and prototyping stage*. During this period, the author iteratively developed a fully functional research prototype that integrates Shelly smart outlets with a Raspberry Pi running Home Assistant [8], [61] to provide real-time tracking and personalized interfaces[60].

Key design features address the specific challenges identified in user research: member-specific consumption tracking enables individual accountability [4], [6], animated visualizations maintain engagement [78], [12], historical data analysis reveals behavioral patterns [33], [26], and automated notifications ensure continued awareness [17], [7]. The dashboard transforms energy monitoring from a passive observation tool into an interactive experience that promotes reflection, discussion, and behavior change within the household context.[20], [37], [79]

The final phase of the research consisted of a *summative evaluation* where the system was deployed in a real-world setting for several weeks. This field study took place within the author's own household, involving two children, the father, and occasionally the grandmother. Participants used the device in their daily routines and shared their experiences through interviews, while the system recorded usage via log-file analysis.

A notable aspect of this evaluation is its *autoethnographic nature*, as the author acted as both the lead researcher and an active participant within the family unit. This approach provided unique advantages, such as a heightened sensitivity to the needs of this specific household and the ability to gain deep, authentic insights into family dynamics that an outside observer might miss. However, this method also presents challenges, including the potential for subjectivity in data interpretation. These autoethnographic elements, along with their impact on the research findings, are carefully discussed and reflected upon in the later sections of this thesis.

This multi-phased approach, moving from broad interviews to an in-depth, autoethnographic field study, aims to capture both the technical and social dimensions of domestic energy use. The corresponding research questions addressed in this thesis are presented in the following section.

1.1. Research Questions

To investigate the challenges and opportunities of family-centered energy monitoring, this thesis is guided by the following six research questions (RQs):

RQ1: How can interactive technologies educate families about their energy consumption and promote sustainable behaviors?

Energy consumption remains largely invisible in everyday life [20], [33]. While smart meters and mobile apps provide raw data, they rarely support interpretation, learning, or behavioral reflection [63], [33]. Families often receive delayed and abstract feedback (e.g., monthly bills), which fails to link actions to outcomes [20], [63]. This research question focuses on the educational potential of interactive systems, how dashboards, visualizations, and real-time feedback can turn energy monitoring into a learning experience [37], [47]. The goal is to understand how interactive representations of energy data can cultivate energy literacy: the awareness and understanding needed to make informed, sustainable choices [37], [23]. In this context, the dashboard is not just a monitoring tool but an educational medium, encouraging users to explore their habits, question their assumptions, and adjust their daily routines [20], [56].

RQ2: What are the differing needs, motivations, and interaction preferences of adults, children, and elderly family members regarding energy literacy?

Households are not homogenous [79], [39]. Adults, children, and older family members vary widely in their digital competencies, motivational triggers, and cognitive capacities [34], [19]. Adults may seek control and optimization, focusing on cost reduction or automation [74], [3]. Children are often visual learners who respond to gamified or playful interfaces [42], [59], while older adults may prefer clarity and simplicity over dense analytics [34], [19]. Recognizing these contrasts is crucial for ensuring inclusivity and engagement [48], [70]. This question explores how design elements such as color schemes, metaphors, data granularity, and interaction styles can be tailored to different user groups without fragmenting the overall family experience [70], [78]. Understanding these user differences is central to designing an interface that is universally usable yet personally meaningful [70], [64].

RQ3: How appropriate are smart switches and IoT devices in capturing accurate and usable energy consumption data for household monitoring?

Accurate data forms the backbone of trust and engagement in energy systems [26], [25]. If the data is unreliable or inconsistent, users quickly lose confidence in the system [33], [26]. This research question evaluates the technical validity of the chosen IoT infrastructure, specifically, the Shelly smart outlets and Raspberry Pi based data collection system [8], [61]. The study compares the data collected from these smart switches against readings from the household's official utility smart meter to assess accuracy, latency, and consistency [26], [30]. Establishing data reliability is essential not only for analytical integrity but also for maintaining user trust particularly when the system is designed for long-term behavioral engagement [33], [25].

RQ4: What advantages and challenges can be uncovered when smart-switch-based energy energy monitoring systems are deployed in real domestic environments?

While controlled laboratory studies offer ideal conditions, real-world family environments introduce numerous contextual complexities [39], [71]. Wi-Fi instability, device malfunctions, cost barriers, privacy concerns, and differing user motivations all affect system performance and adoption [8], [71]. This question investigates the practical feasibility of the system in real domestic settings [33], [52] as well as the users' lived experiences. Advantages may include increased engagement, energy savings, and cost awareness [20], [25], while challenges may involve usability issues, technical maintenance, or user resistance [48], [70]. By studying both sides, this research aims to identify not only what works, but also the barriers that limit long-term adoption of smart energy solutions in everyday homes [74], [52].

RQ5: How can interface design foster collaboration, discussion, and healthy competition around energy use within families?

Energy consumption is not just an individual behavior, it is shaped by shared routines, negotiations, and social dynamics [39], [71]. Families decide collectively when to use appliances, how to balance comfort with efficiency, and how to share responsibilities [79] [39]. This question explores how interaction design can support social engagement around energy use [56], [78]. The dashboard introduces features such as member-specific tracking, comparison charts, and visual avatars that promote both collaboration and friendly competition [4], [6]. By examining how these features influence motivation, communication, and shared accountability, the study seeks to understand how technology can make energy saving a collective, enjoyable family practice rather than a solitary obligation [79], [74].

RQ6: What user-centered design principles can be derived from this study to inform future family-oriented energy management systems?

Finally, the research aims to synthesize empirical findings into actionable design principles for future development [55], [64]. These principles will articulate how to balance simplicity and depth, individual and shared engagement, and aesthetic appeal and usability in family-oriented systems [70], [78]. This question extends the study's impact beyond the prototype itself, offering generalizable insights for designers and researchers in the fields of HCI, sustainability, and smart home technologies [56], [49]. The goal is to produce a framework that others can build upon to create systems that are not only technologically robust but also emotionally engaging and socially meaningful[23], [71].

1.2. Research Contributions

1.2.1. Novel family-centered dashboard design

This research introduces a family-centered energy dashboard that combines networking technology and HCI design to help families better understand and manage their energy use [56], [49]. Instead of treating the home as a single user system, the dashboard views it as a connected network of people and devices, where each family member's actions influence the others [79], [39].

The system gathers real-time energy data from smart meters, connected appliances, and sensors through the home network [8], [30]. This data is displayed in a way that is easy to understand and personally relevant [70], [78]. For example, while parents might see detailed graphs and cost statistics as per their priority, children could see gamified visuals as they immediately focus on interactive objects showing how their actions save energy, rather than informative visualizations [42], [59]. These personalized yet connected views encourage shared responsibility and communication as well as building a healthy competition [4], [6].

From a networking perspective, the dashboard uses a distributed data model that processes most data locally within the home [8], [30]. This approach reduces delays, improves system speed, and protects privacy, since personal usage data does not always need to leave the home network [8], [71]. The system can still connect to cloud services when needed but gives users control over what is shared [30], [71].

The main contribution of this design is how it links technical networking architecture with social interaction design [56], [78]. It shows that smart home technologies can go beyond automation and support collaboration, awareness, and learning among family members through clear, context-sensitive interfaces [37], [79].

1.2.2. HCI insights for energy management systems

The project contributes to HCI research by providing new insights into how people interact with energy management systems [70], [55]. Through multiple rounds of prototyping explored what makes people actually use and trust these systems in daily life [56], [39].

One key insight is that data alone is not enough to motivate engagement [20], [47]. While traditional systems focus on technical accuracy, this research shows that the way data is presented and framed matters more [78], [37]. People are more likely to care about energy consumption when information is relatable, simple, and social [74], [79].

The research also highlights the tension between complexity and usability [70], [76]. Too much detail can overwhelm users, while oversimplified feedback can make them lose interest [76], [78]. The solution is adaptive visualization adjusting the level of detail based on the user's role and familiarity [70], [78]. This approach helps all family members, regardless of age or technical background, engage meaningfully with the system [70], [64].

This work shows that good technical connectivity is not the same as good human connectivity [78], [49]. A system can transfer data efficiently but still fail if people do not understand or relate to the information [20] [47]. Therefore, energy networks must be designed with both technical flow and human communication in mind [56], [79]. These insights expand HCI understanding of interactive, human-centered energy systems that promote cooperation and awareness instead of passive monitoring [37], [55].

1.2.3. Field study findings on multi-generational engagement

A six-week field study was conducted in a household to observe how the family-centered dashboard influenced real-life behavior and communication [33], [39]. The study found that the dashboard encouraged multi-generational engagement, meaning that family members of different ages participated in energy awareness in their own ways [39], [29].

Parents often acted as coordinators who explained or discussed data, while children used gamified features to track progress and remind others about saving energy [42], [59]. Older family members, who were less confident with technology, preferred simple displays or voice-based feedback [34], [19]. Over time, this created shared learning experiences, where younger members helped older ones use the system, and everyone became more aware of their collective impact [23], [29].

From a networking research angle, the field study also tested how the system performed under real conditions [8], [30]. The distributed local network proved to be stable and reliable, even during internet interruptions, since most data was processed within the home. This resilience demonstrated how edge computing can improve both user experience and privacy in household systems [30], [71].

These findings show that multi-generational engagement can be intentionally designed through thoughtful integration of networking and HCI principles [56], [39]. By aligning system performance, data delivery, and interface timing with everyday family routines, the dashboard became part of daily communication rather than a separate tool [37], [79].

Overall, this research offers a practical framework for building family-centered, networked HCI systems that support both technological efficiency and social interaction [56], [49]. It demonstrates that real progress in home energy management comes not only from smart devices or data, but from human connections built around shared, interactive technology [74], [71].

1.3. Thesis Structure

This thesis is structured into six chapters, each addressing a specific dimension of the research and collectively demonstrating how principles of HCI and networking can be leveraged to foster family-centered energy awareness within domestic environments.

Chapter 1 – Introduction establishes the foundation of the research by outlining the context, motivation, and significance of energy literacy at the household level. It presents the research problem, objectives, and questions, emphasizing the need for inclusive, interactive, and network-integrated systems that bridge the gap between technical data and user understanding. The chapter concludes by summarizing the primary contributions and outlining the structure of the thesis.

Chapter 2 – Literature Review critically examines prior work in the domains of smart home technologies, energy management systems, and HCI. It reviews contemporary approaches to energy visualization, user engagement, and behavioral change, highlighting limitations in addressing multi-generational household dynamics. This chapter also explores the role of IoT networking infrastructures in enabling real-time data communication and contextual feedback, thereby identifying key research gaps that motivate the proposed system.

Chapter 3 – Methodology details the research design, emphasizing the user-centered design (UCD) approach adopted throughout the study. It explains the three-phase process, user research, system prototyping, and evaluation, while describing participant recruitment, data collection methods, and analytical frameworks. Furthermore, this chapter provides a technical overview of the system's networking setup, including the integration of Shelly smart switches with a Raspberry Pi through the Home Assistant platform, ensuring secure and reliable data transmission.

Chapter 4 – System Design and Implementation presents the architecture and development of the interactive dashboard. It discusses the integration of IoT devices, data handling protocols, and interface design principles applied to accommodate users of different age groups and technological proficiencies. The chapter emphasizes the alignment of design choices with HCI principles such as usability, accessibility, and feedback responsiveness.

Chapter 5 – Results and Discussion analyzes both technical and behavioral outcomes derived from user testing and field deployment. It interprets user engagement patterns, energy awareness improvements, and system reliability, linking findings to theoretical models of HCI and sustainable interaction design. The discussion synthesizes these results to demonstrate the system's contribution to fostering family-based engagement with energy data.

Chapter 6 – Conclusion and Future Work summarize the major findings, theoretical implications, and practical contributions of the research. It reflects on the integration of networking and HCI in the design of energy monitoring systems and outlines potential avenues for future research, including scalability, personalization, and long-term behavioral impact.

Together, these chapters articulate a coherent narrative demonstrating how human-centered design and networking infrastructures can jointly advance energy literacy and sustainability within modern households.

2. Literature Review

This chapter reviews existing literature across three interrelated domains that collectively inform the design and evaluation of a family-centered energy management system. First, it explores the evolution of smart home technologies and energy monitoring systems [49], [9], forming the technological backbone upon which this research is built. Second, it examines key principles from HCI and their application in sustainability-oriented systems [37], [70], identifying design frameworks that enhance energy awareness and usability across diverse user groups. Third, it considers family-centered technology design [39], [58], analyzing the social and generational factors that influence technology adoption and engagement within households. Finally, the chapter aims to synthesize insights from these domains to identify current research gaps, particularly the lack of inclusive, interactive, and behaviorally informed approaches to energy visualization [47], [78] and to position this thesis within that interdisciplinary space.

2.1. Smart Home Technology and Energy Management

Smart home technology represents a central pillar of the Internet of Things (IoT), transforming ordinary living environments into interconnected, responsive ecosystems [9], [11]. These technologies enable users to remotely access, monitor, and control household appliances and systems, offering both convenience and efficiency [11], [69]. At their core, IoT-based smart devices such as smart plugs, switches, and sensors extend the boundaries of physical space by allowing real-time control even in the absence of the user.

In the context of this research, smart home technologies are not treated merely as convenience tools but as enablers of energy awareness and sustainability [37], [74]. By integrating all family-owned smart devices under a unified web-based dashboard, the system allows users to observe and manage collective energy consumption patterns [33], [49]. This integration ensures that energy use becomes a shared household activity, accessible and comprehensible across all age groups from children learning about sustainability to older adults seeking simplified control.

The transition from luxury to necessity in smart home systems underscores their growing role in promoting energy efficiency [74], [11]. As global energy demands rise, every small behavioral shift such as switching off unused devices or scheduling low-energy periods contributes meaningfully to sustainability [45], [25]. Thus, this section focuses on how smart home technologies, energy monitoring methods, and system integration can collectively foster environmentally conscious habits while maintaining usability and inclusivity for all household members.

2.1.1. IoT devices and smart switches

The evolution of smart home technologies represents one of the most significant advancements within the broader field of the Internet of Things (IoT) [9], [11]. Smart home devices have transitioned from luxury innovations to essential components of modern living, enabling remote control, automation, and monitoring of household systems. Historically, the concept of home automation emerged with the X10 protocol in the 1970s, which allowed rudimentary remote switching of devices over power lines. However, the modern IoT revolution of the 2010s driven by ubiquitous connectivity, affordable microcontrollers, and cloud services transformed home automation into a scalable and interoperable ecosystem.

Smart switches, as a subset of IoT devices, serve as the fundamental interface between users and household appliances. They integrate wireless communication protocols such as Wi-Fi, Zigbee, Z-Wave, and Bluetooth to enable seamless remote operation [69], [9]. In addition to basic on/off control, modern switches support features like scheduling, automation routines, and integration with popular voice assistants such as Amazon Alexa and Google Home. This convergence of hardware and software enables adaptive environments that respond to user preferences while promoting energy efficiency.

In this research, we employ Shelly smart switches, a plug-and-play solution offering robust device-level monitoring and easy installation without complex rewiring. Shelly devices communicate via the MQTT protocol, ensuring low-latency, lightweight data transfer suitable for continuous monitoring [11]. The system is orchestrated through Home Assistant, an open-source integration platform that unifies all devices within a single interface accessible through a web dashboard. A Raspberry Pi serves as the local controller, hosting the MQTT broker and managing RESTful API calls to transmit sensor data for visualization and analysis [8] .

By unifying all smart devices under a common infrastructure, this configuration not only enhances control and reliability but also democratizes access for users of all age groups within a household. This technological foundation supports the overarching goal of fostering sustainable energy behaviors through transparency and interaction.

2.1.2. Energy monitoring technologies

Energy monitoring technologies have evolved to provide increasingly granular insight into household electricity usage, forming the backbone of energy-aware smart systems. They can be broadly categorized into three primary types: whole-home monitoring, device-level monitoring, and non-intrusive load monitoring (NILM) [33], [81].

Whole-home monitoring technologies such as utility-provided smart meters or clamp-on current sensors capture the total household energy consumption. These systems provide a macroscopic view of usage trends and peak demands but often lack the granularity required for appliance-level insights. In contrast, device-level monitoring, which includes smart plugs and switches with integrated energy measurement (such as Shelly devices), enables precise tracking of individual appliance behavior. This approach generates actionable feedback by identifying high-consumption devices and supporting personalized recommendations for energy reduction [81]. However, it requires multiple sensors, resulting in increased cost and setup complexity.

Non-intrusive load monitoring (NILM) attempts to address this trade-off by using a single measurement point to infer individual device usage through signal disaggregation algorithms. Employing techniques from machine learning and signal processing, NILM estimates the operational state and energy consumption of each appliance from aggregate data. Although promising, NILM systems currently face limitations in accuracy, especially in complex multi-device environments with overlapping signatures [26], [82].

Energy data captured from these systems typically include real-time power consumption (Watts), cumulative energy use (kWh), voltage and current measurements, and historical patterns over time. Modern systems also estimate costs based on usage and local tariff data. Data are either stored locally improving privacy and control or in the cloud to enable remote access and analytics. Communication between sensors and control hubs may occur at varying frequencies depending on system constraints, balancing responsiveness with data volume management.

Accuracy remains a critical concern in energy monitoring. Factors such as calibration, sensor precision, and environmental noise can influence measurement quality [26], [68]. Hence, in designing a household system that spans multiple users and devices, achieving a balance between cost, usability, and accuracy is essential to ensure that collected data remains both reliable and meaningful for visualization and feedback.

2.1.3. Integration challenges and opportunities

Integrating diverse smart home devices into a coherent and reliable ecosystem presents both technical and human-centered challenges. One of the principal difficulties lies in interoperability the ability of devices from different manufacturers to communicate seamlessly [38]. Varying communication standards (Wi-Fi, Zigbee, Z-Wave, MQTT, and proprietary APIs) often lead to fragmented systems that are complex for end-users to manage [69], [44]. Open-source platforms like Home Assistant mitigate this issue by acting as middleware, bridging disparate devices and protocols through standardized integrations and automation rules .

Another major challenge involves data synchronization and reliability. Inconsistent network connectivity or device firmware issues can lead to data gaps, inaccurate readings, or command delays. For systems designed for multi-generational families, reliability is especially critical users must trust that devices reflect the true state of their environment. Locally hosted solutions (e.g., using a Raspberry Pi) help reduce cloud dependency, ensuring real-time control even in cases of internet disruption.

Privacy and data security also pose significant integration concerns. Continuous monitoring generates sensitive information about daily routines, occupancy patterns, and energy habits [73], [67]. Ensuring that data remain encrypted, anonymized, and under user control is essential to maintaining trust and encouraging adoption.

Despite these challenges, integration offers powerful opportunities. A unified system can enable cross-device automation, where insights from energy monitoring directly inform control decisions such as automatically turning off idle appliances or providing tailored energy-saving recommendations. Furthermore, by visualizing integrated data through an intuitive dashboard, the system empowers all family members to understand and participate in energy conservation.

Overall, successful integration is not merely a technical endeavor but a foundation for user engagement and sustainability, bridging the gap between advanced IoT infrastructure and meaningful human behavior change [67].

2.2. HCI in Energy Systems

Technology alone does not change human behavior. Even the most advanced smart systems or energy-efficient devices cannot achieve meaningful impact unless they successfully engage users and motivate them to act differently [74], [25]. This is where the field of Human–Computer Interaction (HCI) becomes crucial bridging the gap between technical potential and real-world behavioral outcomes. While energy monitoring tools can collect vast amounts of data, their effectiveness depends on whether users can understand, interpret, and apply that information in daily life. Therefore, the design of such systems must go beyond functionality to address how people think, feel, and interact with technology in the context of sustainability.

This section explores how HCI principles can inform the design of effective and engaging energy systems. It first focuses on user-centered design (UCD) principles, emphasizing the importance of building systems around real user needs, contexts, and abilities rather than technological possibilities alone. Through methods such as interviews, iterative prototyping, and participatory design, developers can ensure that energy interfaces align with household routines and cognitive preferences [70], [64]. For this project, the user research phase conducted with participants from diverse age groups was essential to uncover how families currently perceive energy use, what motivates them to save, and what barriers prevent engagement.

The next focus is on interface design for energy awareness, where the visual and interactive components play a defining role in system adoption. An intuitive, engaging interface transforms invisible energy data into something tangible and actionable [37], [47], [78]. For example, using color-coded indicators, gamified feedback, or simplified dashboards can appeal to different user motivations children respond to playfulness, adults to analytics, and older users to clarity and simplicity.

Finally, the section discusses usability considerations for diverse user groups, highlighting that technical capability often differs from user adoption. Designing for multi-generational households requires balancing accessibility, personalization, and complexity. An appealing interface ensures that users remain engaged over time; without it, even the most accurate data systems risk being ignored.

In summary, this section situates HCI as the critical factor that converts technical innovation into behavioral change transforming energy monitoring from a passive task into an interactive, educational, and sustainable household practice.

2.2.1. User-centered design principles

User-Centered Design (UCD) is a foundational principle within Human–Computer Interaction that prioritizes the needs, preferences, and contexts of users throughout all stages of system development. Rather than starting from technical capabilities, UCD begins by understanding how people live, think, and interact with technology, ensuring that the resulting product aligns with their real-world behaviors and expectations [55], [64]. In the context of energy management systems, this approach is essential, as the effectiveness of a system depends not only on its accuracy or reliability but on how intuitively it supports users in understanding and acting upon their energy consumption patterns.

The UCD process generally follows five iterative stages: understanding users and their contexts, specifying user requirements, designing solutions, evaluating against requirements, and refining based on feedback. In this research, these stages were operationalized through a mixed-methods approach combining qualitative and technical inquiry. To understand users and their contexts, semi-structured interviews were conducted with 16 participants across six family households, each representing diverse age groups and levels of technical literacy. The study sought to explore how family members perceive energy use, their existing awareness of consumption, and the barriers they face when engaging with technology.

Following data collection, the results were analyzed using Braun and Clarke's (2006) thematic analysis framework [64], which enabled the identification of recurring patterns, motivations, and frustrations related to energy consumption and smart home interactions. These insights informed the requirements specification phase, translating user observations into actionable design criteria. For instance, participants emphasized the need for clear visualization, minimal technical jargon, and interfaces that appeal across generations.

Based on these findings, the design phase produced a web-based dashboard integrating real-time monitoring and historical insights, tailored to household needs. Iterative testing with participants ensured that design adjustments were guided by user feedback rather than assumptions. This cyclical process of evaluation and refinement exemplifies UCD's strength ensuring that technology evolves with its users. Ultimately, applying user-centered design principles allowed this research to create a system that is not only technically sound but also contextually meaningful, usable, and engaging for families in their everyday lives.

2.2.2. Interface design for energy awareness

Designing effective interfaces for energy awareness presents unique challenges due to the abstract and intangible nature of electricity. Unlike other resources, energy cannot be directly perceived, and its primary unit of measurement the kilowatt-hour (kWh) lacks intuitive meaning for most users [20], [33]. Consequently, users often struggle to relate everyday actions to their energy consumption, as feedback typically arrives in delayed forms such as monthly bills. This abstraction obscures causal links between behavior and impact, reducing motivation for change.

Cognitive barriers further complicate comprehension. Energy use involves temporal dimensions when consumption occurs and spatial dimensions where and by which devices energy is used. Establishing these relationships often requires complex mental calculations, making it difficult for users to identify which specific actions contribute to consumption peaks or inefficiencies.

To address these issues, interface design strategies for energy awareness must make the invisible visible, contextualize data, and deliver actionable insights rather than raw metrics. Visibility strategies include real-time feedback displays that show instantaneous consumption, ambient visual cues for peripheral awareness, and historical comparisons that allow users to track progress over time [47], [33]. Device-level breakdowns and visual metaphors such as speedometers or fuel gauges help bridge the gap between data and perception.

Contextualization enhances relevance by translating kWh into tangible equivalents, such as cost in local currency or environmental impact in CO_2 emissions [37], [74]. Social comparison features that show how a household's usage ranks among similar users can motivate behavioral change. Similarly, integrating temporal contexts like time of day or day of week helps users understand patterns and adjust habits accordingly.

Providing actionable insights transforms awareness into meaningful engagement. Interfaces that include energy-saving recommendations, anomaly detection, and alerts for unusual activity promote proactive behavior. Features such as peak usage identification, device efficiency rankings, and predictive analytics empower users to make informed decisions.

Empirical studies highlight that the type, frequency, and granularity of feedback critically affect user engagement. Real-time, device-level feedback tends to yield more persistent behavior change than aggregated or delayed reports. Effective visualizations, goal-setting elements, and social or gamified components have been shown to enhance motivation and comprehension [6], [57].

Finally, robust information architecture supports diverse user needs through layered complexity. Dashboards provide accessible overviews, while detailed views and filtering options cater to advanced users, ensuring both simplicity and depth within the same interface framework.

2.2.3. Usability considerations for diverse user groups

Designing energy management systems for family households requires accommodating a wide range of users with differing cognitive, physical, and motivational characteristics. Households are inherently diverse environments, where age, experience, and goals influence how individuals interact with technology. A truly usable system must therefore adapt to this diversity through flexible design that supports accessibility, comprehension, and engagement across generations.

Age-related differences are among the most significant factors shaping interaction [34], [19]. For children (6–12 years), limited reading skills and short attention spans necessitate highly visual and interactive interfaces. Game-like elements, vibrant colors, and simple feedback loops promote learning through exploration and play. Teenagers (13–17 years), often more technologically adept, expect fast, mobile-first interfaces that align with their digital habits. They are motivated by social comparison features but are also conscious of privacy and control. Adults (18–65 years) typically focus on practicality, seeking tools that facilitate cost savings, convenience, and automation while balancing varying levels of technical literacy and limited time. Elderly users (65+) may experience visual or motor limitations and show lower acceptance of new technologies. For this group, clarity, simplicity, and consistent guidance are essential to reduce cognitive load and resistance to use [70], [78].

Beyond age, technical literacy represents another spectrum of diversity. Novice users require structured guidance and clear instructions, while intermediate users prioritize efficiency, and expert users seek deeper customization and control. The design challenge lies in accommodating all these groups without overcomplicating the interface a goal achievable through progressive disclosure, adaptive interfaces, and customizable dashboards.

Finally, users' motivations for engaging with energy dashboards vary. Some focus on economic incentives (cost reduction), others on environmental awareness, curiosity about their consumption, or a desire for control over household devices [74], [3]. Incorporating motivational diversity into usability design through personalization, rewards, and meaningful feedback enhances engagement and ensures sustained interaction across all user segments.

2.3. Family-Centered Technology Design

2.3.1. Multi-generational user needs

Family-centered technology design recognizes that households function as complex social units where technology must serve multiple users simultaneously, each bringing distinct needs, competencies, and expectations [58]. Unlike single-user systems, family technologies must accommodate diverse age groups, technical literacies, and motivational structures within the same interface. Adults typically prioritize functionality, cost control, and automation, seeking clear metrics that translate energy data into financial impact. Children respond more readily to visual immediacy and playful interaction, where energy consumption becomes a game rather than abstract statistics. Elderly family members often require maximal simplicity, with large text, high contrast, and minimal cognitive demands to overcome potential technophobia or sensory limitations.

This diversity creates design tension between depth and accessibility. A dashboard showing detailed kWh breakdowns and cost projections satisfies analytical adults but overwhelms younger users, while cartoonish gamified displays entertain children but appear juvenile to parents. The solution lies in layered interfaces that provide universal entry points while offering progressive disclosure for advanced exploration. Core household metrics remain prominently visible to all, while individual user profiles unlock personalized views based on login or device recognition. This approach ensures that every family member encounters familiar, age-appropriate representations of the same underlying data.

Research consistently demonstrates that multi-generational design succeeds when it leverages existing household roles and communication patterns. Parents naturally assume coordinator functions, explaining dashboard insights to children during shared viewing sessions. Children, in turn, often become system advocates, reminding others about energy-saving opportunities discovered through gamified feedback. These organic dynamics suggest that family technologies should facilitate rather than dictate interaction, providing shared spaces for collective discussion alongside private areas for individual reflection. By mapping design decisions to observed family structures, systems become embedded in daily routines rather than external impositions

2.3.2. Social dynamics in household technology adoption

Household technology adoption rarely follows linear paths but emerges through negotiation, influence, and shared decision-making among family members. Technical champions - typically teenagers or tech-savvy adults - often drive initial adoption, demonstrating functionality and resolving setup issues. However, sustained engagement requires broader buy-in, where less enthusiastic members perceive personal value or social reinforcement. Resistance frequently stems from perceived complexity, privacy concerns, or irrelevance to daily priorities, underscoring the need for intuitive onboarding and immediate demonstrable benefits.

Social influence plays a crucial role in normalizing technology use. When respected family members visibly engage with a system, others follow suit, creating virtuous adoption cycles [58]. Conversely, vocal skepticism from influential members can undermine collective participation. Design must therefore anticipate these dynamics by incorporating low-risk entry points that demonstrate value without demanding commitment.

Family power structures also shape interaction patterns. Decision-makers who control finances respond strongly to cost projections, while routine managers prioritize convenience features like automated scheduling. Children influence through persistence and peer reinforcement, often becoming unexpected advocates for sustainability features. Effective designs map functionality to these influence patterns, ensuring that each member's engagement reinforces collective adoption. Shared dashboards become discussion catalysts, transforming data viewing into family conversations about priorities, habits, and shared goals.

Privacy dynamics add complexity to family systems. While collective energy tracking promotes accountability, individual usage profiles risk embarrassment or conflict. Transparent usage attribution must balance motivational transparency with dignity preservation, allowing opt-out options or anonymized aggregate views when preferred. These social considerations elevate family-centered design beyond technical implementation, requiring deep understanding of household negotiation patterns and relationship structures.

2.3.3. Gamification and engagement strategies

Gamification—the application of game design elements to non-game contexts has emerged as a popular strategy for increasing engagement with energy monitoring systems, particularly for younger users. Research on gamified energy dashboards has identified several mechanisms through which game elements can influence behavior. Points systems that reward energy savings provide immediate, tangible feedback that makes abstract consumption reductions concrete and trackable. Achievement badges for reaching milestones create intermediate goals that maintain motivation beyond simple cost savings. Leaderboards introduce social comparison in structured formats, enabling both within-family competition and comparisons with neighbors or similar households.

However, research reveals important limitations and potential pitfalls of gamification in energy contexts. The novelty effect represents a persistent challenge, as initial enthusiasm for games and competitions often wanes after weeks or months of use. Studies tracking long-term engagement with gamified energy systems show declining interaction rates over time, suggesting that extrinsic motivators like points may not sustain behavior change once the game loses its appeal [20]. Furthermore, gamification risks trivializing serious environmental concerns or fostering focus on game mechanics rather than genuine understanding of energy consumption and its environmental impacts.

Age-specific responses to gamification further complicate design decisions. While younger children respond enthusiastically to games, badges, and visual rewards, teenagers may find such elements childish or gimmicky. Adults typically prioritize functionality over entertainment, though many appreciate lighthearted elements that reduce the sense of obligation around energy monitoring. This diversity suggests that effective gamification must be optional and customizable, allowing family members to engage with the system according to their preferences rather than forcing all users into game-based interactions.

Recent research has explored more sophisticated engagement strategies that move beyond simple gamification toward meaningful integration of energy awareness into daily family life [20]. Ambient displays that provide peripheral awareness without demanding active attention, personalized insights that highlight patterns specific to each household, and narrative elements that tell stories about the family's energy journey represent promising alternatives to traditional game mechanics. The key insight across approaches is that sustained engagement requires systems to provide ongoing value whether through genuine utility, continued learning, or emotional connection rather than relying solely on novelty or external rewards.

For the current research, these insights inform the design of a dashboard that accommodates multi-generational needs through flexible complexity levels, harnesses positive family dynamics through collaborative features while respecting individual privacy, and incorporates engagement elements that can sustain interest beyond initial deployment. The challenge lies in creating a system that serves as both a practical household management tool and a platform for family learning and collective action toward energy conservation.

2.4. Data Visualization for Energy Consumption

The challenge of making energy consumption comprehensible and actionable fundamentally depends on effective data visualization. Raw energy data in kilowatt-hours, instantaneous power measurements, cumulative consumption remains meaningless to most users without translation into visual forms that support pattern recognition, comparison, and decision-making [57]. As Batch and Elmqvist note, the interactive visualization gap in exploratory data analysis is particularly pronounced in sustainability contexts, where users lack baseline knowledge against which to interpret numerical values. This section examines visualization techniques proven effective for energy data, explores the role of interactivity in supporting user engagement, and reviews evidence on how different presentation methods influence actual behavior change.

2.4.1. Effective visualization techniques

Energy visualization research has identified distinct categories of visual representation, each serving different analytical purposes. Temporal visualizations address the critical question of when energy is consumed, revealing daily patterns, weekly cycles, and seasonal variations. Line graphs remain the most familiar temporal format, enabling users to track consumption trends over hours, days, or months. However, research by Brehmer et al. on timeline design demonstrates that conventional line graphs can become cluttered and difficult to interpret when displaying multiple data series or comparing across time periods[?]. Heat maps offer an alternative temporal representation, using color intensity to show consumption levels across a calendar grid, making it immediately apparent which days or hours exhibit unusually high usage. These visualizations prove particularly effective for identifying anomalies the forgotten appliance left running overnight appears as an unexpected bright spot in an otherwise dark pattern.

Radial or circular charts represent time in cyclical format, naturally mapping the 24-hour day onto a clock face. While less familiar to general users, these visualizations excel at revealing recurring patterns the evening consumption peak appears at the same radial position each day, making habitual behaviors immediately visible. Research by Karjalainen examining consumer preferences for energy feedback found that users appreciated multiple complementary views rather than single "best" visualizations, as different formats revealed different insights[36].

Proportional visualizations answer the distinct question of what consumes energy, breaking down total usage into device-level or category-level components. Pie charts, despite criticism in visualization literature for their perceptual limitations[70], remain popular for showing simple breakdowns because users intuitively understand the part-to-whole relationship. Tree maps provide more sophisticated hierarchical breakdowns, enabling nested categorization total consumption divided by room, with each room further divided by device. However, the complexity of tree maps can overwhelm users unfamiliar with this visualization type, suggesting that progressive disclosure starting with simple pie charts and offering tree map details on demand may better serve diverse user populations.

Comparative visualizations enable users to contextualize their consumption against meaningful benchmarks. Sparklines tiny line charts shown inline with device names provide at-a-glance trend indication without consuming significant screen space[?]. Small multiples, where identical chart types are repeated for different devices or time periods, facilitate visual comparison across categories. Bullet graphs compress multiple pieces of information current value, historical average, and target goal into compact horizontal bars that support quick performance assessment. Research demonstrates that comparison features significantly enhance user engagement, as abstract consumption numbers become meaningful only when users can assess whether their usage is high, low, or typical [76].

The selection of appropriate visualization types depends critically on user goals and data characteristics. Real-time monitoring benefits from gauge displays and current-value indicators that emphasize immediate status. Historical analysis requires temporal visualizations that reveal patterns over extended periods. Device comparison needs proportional breakdowns and ranked lists. Effective dashboards therefore employ multiple coordinated visualizations, each optimized for specific analytical tasks while maintaining visual consistency that prevents cognitive overload[57].

2.4.2. Interactive dashboards

Static visualizations, while useful for presenting pre-defined insights, cannot accommodate the diverse questions and exploration paths of different users. Interactive dashboards enable users to manipulate time ranges, filter devices, switch between visualization types, and drill down from overview to detail according to their individual interests and needs [57]. Research on interactive visualization demonstrates that user-controlled exploration leads to better comprehension and retention than passive consumption of pre-digested information[76].

Time range selection represents a foundational interactive feature, allowing users to examine consumption at different temporal granularities today's hourly breakdown, this week's daily totals, this year's monthly trends. Quick preset buttons (today, this week, this month) balance flexibility with convenience, while calendar date pickers enable investigation of specific periods of interest. The ability to overlay multiple time periods comparing this week to last week, or this month to the same month last year supports learning from historical patterns and validation of behavior changes.

Device filtering enables users to focus on subsets of household consumption, isolating major appliances to understand their contribution or examining a single room's devices to assess localized usage. Multi-select capabilities and hierarchical filtering (by room, by device type, by consumption level) provide flexibility for different analytical approaches. Search functionality becomes essential in households with many monitored devices, enabling quick access to specific appliances without scrolling through lengthy lists.

View switching allows users to examine the same data through different visualization lenses. A user might start with a pie chart to identify which device consumes most energy, switch to a line graph to understand when that device runs, then examine a calendar heat map to see if usage patterns vary by day of week. This fluid movement between perspectives, made possible through consistent interface controls and rapid re-rendering, supports the iterative sense-making process through which users develop genuine understanding of their consumption patterns[57].

Coordinated multiple views take interactivity further by linking separate visualizations such that interactions in one view update all others. Selecting a time period in one chart automatically filters all other charts to that period. Clicking a device in a pie chart highlights that device's contribution across all temporal views [20]. This coordination reduces the cognitive burden of maintaining context across separate analyses while revealing relationships that single views cannot show[76]. Research by Batch and Elmqvist demonstrates that coordinated views significantly improve users' ability to answer complex multi-faceted questions about their data.

However, dashboard interactivity must balance power with usability. Excessive features overwhelm novice users, while insufficient capabilities frustrate those seeking deeper analysis. Progressive disclosure presenting essential views and simple controls prominently while making advanced features discoverable but not intrusive helps serve this spectrum[57]. Responsive design ensures dashboards function effectively across devices, from large desktop monitors enabling side-by-side comparisons to mobile phones supporting quick consumption checks[17].

2.4.3. Behavioral impact of different presentation methods

The ultimate measure of visualization effectiveness in energy contexts is behavioral impact do users actually consume less energy after viewing feedback? Research reveals complex relationships between presentation methods and behavior change, mediated by factors including feedback granularity, framing, and temporal immediacy[26].

Feedback granularity research demonstrates that device-level monitoring produces larger consumption reductions than whole-home totals. Hargreaves et al.'s field study found that households with appliance-specific data reduced consumption 12-15% versus 5-7% for whole-home monitoring only. The mechanism appears to be actionability users cannot act on "you used 47 kWh yesterday" but can respond to "your game console used 8 kWh on standby." Visualizations enabling device-level analysis therefore prove more effective than aggregate-only displays, though the additional complexity must be managed through careful interface design[26].

Framing effects influence how users interpret and respond to consumption data. Positive framing ("you saved 3 kWh compared to last week") generates different responses than negative framing ("you wasted 3 kWh more than last week") or neutral presentation ("you used 3 kWh more than last week"). Research on feedback framing in sustainability contexts suggests positive framing sustains engagement better over time, as repeated negative messages can lead to defensiveness or disengagement[18]. However, framing must remain honest—false praise for genuinely high consumption undermines trust and system credibility[76].

Temporal immediacy of feedback strongly affects behavior change potential. Real-time displays enable immediate association between actions and consumption turning on an appliance and seeing power usage increase instantly creates visceral understanding impossible with delayed monthly bills[26]. However, continuous real-time monitoring can become overwhelming, and research shows many users prefer periodic summaries (daily or weekly) that provide reflection opportunities without constant vigilance[76]. Effective systems therefore offer both real-time access for those who want it and periodic automated summaries for those preferring less frequent engagement.

Social comparison elements introduce powerful behavioral motivators but require careful implementation [68]. Opower's large-scale studies demonstrate that showing households how their consumption compares to neighbors drives significant reductions, particularly among high consumers[15]. However, the "boomerang effect" where below-average consumers increase usage toward the average highlights risks of poorly designed social comparisons[18]. Visualizations must frame comparisons to maintain motivation across the consumption spectrum, often through normative messaging that praises low consumers while encouraging high consumers to improve.

The persistence of behavior change represents a critical concern, as many studies document declining engagement and regression toward baseline consumption after initial novelty periods[39]. Visualization strategies that maintain interest include variable content highlighting, where the system rotates featured insights rather than showing identical views daily; progressive goal-setting, where achievements unlock new challenges; and integration with meaningful milestones, such as calculating cumulative environmental impact over time[23]. Research by Frederiks et al. on household energy behavior emphasizes that sustained change requires internalization of new habits rather than continued reliance on external monitoring, suggesting visualizations should ultimately support habit formation rather than perpetual vigilance[7].

2.5. Research Gap and Positioning

The preceding sections have established the technological capabilities of smart home energy monitoring, the HCI principles necessary for effective interface design, the unique challenges of family-centered technology, and the visualization techniques that support energy awareness. However, significant gaps remain between these individual research domains and their integrated application to real household contexts. This section identifies specific limitations in current research and positions the present thesis as addressing these gaps through a novel combination of technical implementation, rigorous HCI design, and autoethnographic family study.

2.5.1. Gaps in Existing Research

Limited Integration of Technology and Interface Design: A significant portion of smart switch and energy monitoring research focuses on technical accuracy, communication protocols, and hardware efficiency, treating interface design as an afterthought. Conversely, HCI research on sustainability often employs simplified or simulated energy data rather than integrating with actual monitoring hardware. Few studies bridge these domains, examining how real-time device-level monitoring from commercial smart switches can be transformed through thoughtful interface design into systems that genuinely support household behavior change [9], [57]. This gap leaves critical questions unanswered: How accurate must monitoring be to support useful feedback? Which technical capabilities matter most for user engagement versus which are invisible to users? How do hardware limitations constrain interface possibilities?

Insufficient Attention to Family Dynamics: Most energy consumption research treats households as single analytical units, aggregating usage without examining internal dynamics. Even studies acknowledging multiple household members typically gather data from one respondent per household, missing the divergent perspectives and needs of different family members. The limited research explicitly addressing families tends to focus on parental control and child education separately rather than examining the full multi-generational ecosystem. This leaves designers without guidance on how to accommodate competing needs, navigate privacy tensions around monitoring, or harness positive family dynamics for collective action. The question of how to design single interfaces serving users ranging from young children to elderly adults remains largely unaddressed in energy contexts.

Underexplored Diversity of User Needs: Energy interface research typically assumes technically literate adult users, with limited consideration of how children, elderly users, or those with varying digital literacy interact with consumption feedback [58]. Age-related research exists in broader HCI literature but has not been systematically applied to energy contexts. The specific challenges of designing energy visualizations for children who lack conceptual understanding of kilowatt-hours and electricity costs remain largely unaddressed. Similarly, accessibility considerations for elderly users or those with visual impairments receive minimal attention in energy dashboard design, despite this population representing significant household decision-makers.

Scarcity of Extended Field Deployments: Laboratory studies and short-term field trials (ranging from days to a few weeks) dominate energy feedback research, providing limited insight into long-term adoption patterns and sustained behavior change [20]. The practical challenges of deploying monitoring hardware in participants' homes, combined with research timeline constraints, result in most studies examining initial reactions rather than the crucial period when novelty fades and systems must deliver sustained value [75]. Longitudinal research tracking households over months or years remains rare, leaving critical gaps in understanding which engagement strategies maintain interest beyond initial curiosity, how energy awareness evolves with continued exposure to feedback, and whether consumption reductions persist or regress over time.

Autoethnographic Approaches Rare in HCI: While autoethnography has valuable precedent in social sciences, its application to HCI research and particularly to smart home studies remains limited. The insider perspective that comes from researchers living with their own designs offers unique insights into everyday use patterns, family negotiations around technology, and the gap between design intentions and lived reality. However, this approach also raises methodological concerns around bias, generalizability, and ethical boundaries when researching one's own family. The HCI field lacks established frameworks for conducting and evaluating autoethnographic technology research, leaving valuable perspectives underutilized.

3. Research Methods

This chapter details the methodological approach employed to investigate how user-centered dashboard design can foster energy awareness and conservation behavior in families. The research adopts an exploratory, mixed-methods design grounded in HCI principles, combining qualitative insights from user interviews with quantitative measurements of system usage and energy consumption [18]. The methodology reflects an iterative design process, where users are not merely research subjects but active contributors whose feedback continuously shapes the evolving system [67]. This chapter outlines the philosophical foundation, study design, data collection procedures, analytical approaches, and ethical considerations that guided the research process. By utilizing autoethnography, this study leverages the researcher's dual position as both participant and analyst to provide a deeply contextualized understanding of family dynamics from the inside out.

3.1. Research Philosophy and Approach

3.1.1. User-centered design methodology

This research is fundamentally grounded in user-centered design (UCD), a conceptual framework that places human needs, capabilities, and contexts at the center of technology development [64], [57]. As articulated by Norman (2013) and operationalized through ISO 9241-210 standards [64], UCD involves iterative cycles of understanding users, specifying requirements, producing design solutions, and evaluating outcomes against user needs [57]. Unlike technology-first approaches that develop solutions and subsequently seek users, UCD begins with deep understanding of the people who will use the system and the problems they face.

For this research, user-centered design manifests in several concrete ways. First, the study commenced with extensive exploratory interviews to understand how families currently think about energy, what motivates conservation behaviors, what barriers prevent action, and what role technology might play in addressing these challenges. These interviews occurred before any design decisions, ensuring that technical solutions emerged from genuine user needs rather than assumptions about what families should want. Second, the prototyping phase involved continuous user feedback, with design iterations driven by participant responses rather than researcher preferences. Features were added, modified, or removed based on whether users found them valuable, understandable, and usable. Third, evaluation criteria centered on user experience metrics comprehension, satisfaction, perceived usefulness alongside technical performance measures.

The user-centered philosophy extends to acknowledging users as experts in their own experiences. While researchers bring expertise in HCI principles and technical implementation, participants possess irreplaceable knowledge about their daily routines, family dynamics, and consumption contexts. This research treats participants as co-designers whose insights are essential rather than incidental to successful outcomes. This collaborative dynamic is a hallmark of participatory design, a framework where the distinction between 'researcher' and 'user' is blurred in favor of a shared design process [1].

This collaborative approach is further enhanced by an autoethnographic dimension, as the researcher is also a member of one of the participating families. By adopting this insider perspective, the study gains access to nuanced daily routines and subtle household constraints that external observation might otherwise overlook [67].

3.1.2. Mixed-methods research rationale

The research employs a mixed-methods approach, integrating qualitative and quantitative data collection and analysis to achieve comprehensive understanding that neither method alone could provide [18], [77]. This methodological pluralism recognizes that different research questions require different evidence types. Understanding why users behave certain ways, what meanings they attribute to their actions, and how they experience the system demands qualitative inquiry through interviews and observations [77]. Determining how much energy consumption changed, how frequently users engaged with the dashboard, and which features attracted most interaction requires quantitative measurement through system logs and usage analytics.

The integration of qualitative and quantitative methods occurs at multiple levels. During data collection, interviews provide context for interpreting quantitative patterns a decline in dashboard checking might reflect satisfied learning rather than disengagement, discernible only through user explanations. During analysis, triangulation between self-reported behaviors from interviews and actual logged behaviors validates findings while revealing interesting discrepancies where perceptions diverge from actions. During interpretation, qualitative insights explain quantitative patterns, while quantitative evidence grounds qualitative claims in measurable outcomes [22].

This mixed-methods approach aligns with pragmatist philosophical traditions that prioritize practical problem-solving over methodological orthodoxy. The research question how to design effective family energy dashboards matters more than adherence to purely qualitative or quantitative paradigms. Different aspects of this question benefit from different methodological tools, and the research flexibly employs whatever methods best address specific sub-questions while maintaining overall coherence through the unifying focus on user-centered design [77].

The autoethnographic component adds a third methodological dimension beyond the qualitative-quantitative binary. Autoethnography contributes reflexive, experiential knowledge from the researcher's dual role as system designer and family user. This insider perspective generates insights about lived experience with the technology that structured interviews and usage logs cannot fully capture the impromptu family conversations sparked by dashboard discoveries, the subtle frustrations with interface quirks, the evolution of system integration into household routines. While autoethnographic data raises questions about researcher bias and generalizability, it provides invaluable depth that strengthens rather than replaces other data sources when appropriately acknowledged and critically examined [22].

3.1.3. Autoethnographic positioning and reflexivity

This research incorporates autoethnography as a methodological approach that combines the researcher's personal experience with systematic analysis of family technology adoption within domestic energy management, situated at the intersection of Indian cultural background and Austrian household economics. As an Indian mother living and implementing this project in Vienna, the researcher occupies a dual role as both system designer/developer and participating family member, providing an insider perspective on cross-cultural domestic technology deployment. This positioning captures how South Asian family values of collective responsibility and resource consciousness translate into Austrian contexts of precise energy billing and sustainability awareness.

The autoethnographic lens reveals unique integration patterns shaped by this cultural-economic juxtaposition [28]. Indian household instincts toward light conservation - turning off switches, monitoring standby loads - align naturally with Austrian emphasis on meter accuracy and tariff optimization, creating intuitive dashboard adoption. Evening family reviews become natural discussion spaces where Indian parenting emphasis on teaching children responsibility merges with Austrian practicality of cost tracking. The researcher's lived experience documents how culturally ingrained habits amplify system effectiveness while navigating local technical realities like Home Assistant firmware updates during Austrian winter blackouts.

Reflexivity critically examines researcher influence across cultural boundaries [28], [32]. As Indian mother, there exists natural tendency toward demonstrative family achievement; as system developer, motivation to validate technical effort; as immigrant navigating Austrian household norms, pressure to prove sustainability competence. Family members might moderate feedback knowing researcher's emotional-cultural investment, while researcher may unconsciously favor interpretations aligning Indian collectivism with observed behaviors.

Mitigation strategies address these layered influences. Individual post-deployment interviews with father, mother (researcher), older child, and younger child capture authentic perspectives, analyzing researcher responses alongside family voices. System logs provide objective triangulation - actual login frequency, feature usage, energy reductions - independent of cultural framing. Research journal documents cross-cultural decision rationales: choosing euro displays for Austrian practicality while maintaining visual metaphors resonating with Indian visual learning traditions. Field notes contrast Indian household habits (manual switching) against dashboard automation acceptance.

This reflexive autoethnographic positioning generates insights impossible through external study: how Indian resourcefulness accelerates Austrian smart home adoption, how cultural communication patterns shape technology discussions, how immigrant mothers leverage dual competencies for household innovation [32]. Triangulated against 16 external interviews, these findings reveal universal family technology principles alongside culturally specific adoption accelerators, contributing nuanced understanding of cross-cultural domestic energy systems grounded in authentic lived experience across Indian-Austrian household realities [22].

3.2. Study Design Overview

The research unfolds across three sequential phases, each building upon insights from previous stages while maintaining flexibility to adapt based on emerging findings [64]. This iterative structure embodies user-centered design principles while enabling both breadth across multiple families and depth through extended engagement with one family.

3.2.1. Three-phase approach

Complete research process showing three sequential phases over 18 weeks. Each phase builds on outputs from previous phases, demonstrating iterative user-centered design methodology. The parallel data collection streams in Phase 3 enable triangulation.

Interviews ⟶ Prototyping ⟶Field study & post-deployment interviews

Phase 1:

Pre-Deployment Interviews: The study begins with semi-structured interviews with 16 participants from diverse family structures to understand current energy awareness, consumption behaviors, attitudes toward smart home technology, and preferences for energy feedback. These interviews serve multiple purposes: identifying user needs that inform system requirements, establishing baseline knowledge and behaviors against which to measure change, and recruiting potential participants for later study phases. Participants include parents, teenagers, and children, ensuring representation across the age spectrum that will use the final system. Interview data undergoes thematic analysis to extract key patterns, needs, and design implications.

Phase 2:

Iterative Prototyping: Drawing on Phase 1 findings, the prototyping phase develops progressive versions of the dashboard interface and underlying system architecture. Early prototypes focus on core functionality displaying real-time consumption, historical trends, and device-level breakdowns with minimal aesthetic refinement. These are shared with subset of interview participants for feedback on comprehension, usefulness, and usability. Subsequent iterations incorporate this feedback, refining visualizations, adjusting information architecture, and adding requested features. This cycle repeats until reaching a stable design that participants consistently describe as understandable and valuable. Prototype evaluation employs think-aloud protocols where users narrate their thought processes while exploring the interface, revealing confusion points and navigation difficulties [72].

Phase 3:

Field Study Deployment and Post-Deployment Family Interviews:. The refined system deploys in the researcher's own household, providing extended real-world testing with the autoethnographic family. This deployment involves installing Shelly smart outlets on major appliances, configuring the Raspberry Pi and Home Assistant integration, and making the dashboard accessible to all family members. The field study generates multiple data streams: automated logging of energy consumption, dashboard access patterns, feature usage, and notification responses; observational notes on family discussions and behaviors around energy; and researcher reflections on the dual role as designer and user. The extended timeline enables examination of how engagement evolves beyond initial novelty, whether behavior changes sustain over time, and how the system integrates into established household routines.

Following the field deployment, individual interviews with each family member capture their experiences, perceived behavior changes, and satisfaction with the system. These interviews employ age-appropriate questioning detailed self-reflexive questions for adults, concrete examples for children to elicit authentic perspectives from all household members. The separation of interviews (rather than group discussion) encourages honest feedback without social desirability bias or dominant voices overshadowing quieter family members. These interviews provide crucial validation of quantitative findings, explanation of usage patterns observed in logs, and identification of usability issues or desired improvements.

This three-phase structure balances breadth and depth: Phase 1 captures diverse perspectives across multiple families, Phases 2 and 3 provide intensive longitudinal engagement with one family. The progression from broad exploration to focused deployment mirrors standard user-centered design processes while the autoethnographic element adds depth impossible in traditional participant studies.

3.3. Data Collection Methods

3.3.1. Semi-structured interviews

The pre-deployment interviews employ semi-structured format, combining predetermined core questions ensuring consistency across participants with flexibility to explore unexpected topics that emerge during conversation. This approach balances the systematic data collection needed for thematic analysis with the responsiveness to individual experiences that yields rich insights [16].

The interview protocol begins with warm-up questions establishing rapport and gathering demographic context: household composition, primary decision-makers for household management, general technology comfort levels. The core interview explores five main themes: current energy awareness ("How much do you think about your household's energy use?"), consumption behaviors ("Can you walk me through your typical day and point out when you think about energy?"), existing strategies for managing usage ("What do you currently do to try to save energy?"), attitudes toward monitoring ("How would you feel about having detailed data on your energy consumption?"), and technology preferences ("What kind of information would be most useful to you?").

For adult participants, questions probe motivations financial savings, environmental concern, household management and barriers to conservation. For child participants, questions use age-appropriate language and concrete scenarios: "If you could see how much energy your game console uses, would that make you want to turn it off more?" Interviews with teenagers address privacy concerns more explicitly, recognizing this age group's heightened sensitivity to monitoring.

All interviews are audio recorded with participant consent (Please refer to the Appendix A.1) and transcribed verbatim for analysis. Interviewer field notes capture non-verbal cues, emotional responses, and environmental context not evident in transcripts.

3.3.2. Prototype testing sessions

Prototype testing employs think-aloud protocol, where participants verbalize their thoughts while interacting with dashboard prototypes. This method, established in HCI usability research, reveals users' mental models, confusion points, and decision-making processes that observation alone cannot capture. Testing occurs with 4-6 participants from the interview pool, selected to represent diverse technical literacy levels and household roles (parents, teenagers, children).

Each testing session presents participants with realistic scenarios: "You want to see which device used the most energy yesterday show me how you would find that information." As participants navigate the prototype, they describe what they're looking at, what they expect will happen when they click elements, and how they interpret displayed information. The researcher remains silent except to prompt continued narration if participants fall quiet, avoiding leading questions or hints that would mask usability problems.

Post-interaction, brief interviews probe participants' overall impressions, perceived usefulness of features, and suggestions for improvements. The iterative nature means early sessions identify major usability flaws addressed in subsequent prototype versions, while later sessions validate refinements and catch subtle remaining issues.

3.3.3. Field study methodology

The field study combines multiple data collection methods to triangulate findings and capture both objective behaviors and subjective experiences [22], [18], [39]. The primary household serves as the deployment site, with the researcher (mother) maintaining both participant and observer roles.

Technical Data Logging:

The system automatically captures timestamped records of all energy consumption (device-level and total), dashboard access events (who logged in when and from which device), feature interactions (which visualizations viewed, which controls used), and notification deliveries and responses. This produces rich quantitative data enabling analysis of usage patterns, engagement evolution, and correlations between dashboard checking and consumption changes [16].

Observational Field Notes:
The researcher maintains a research journal documenting family interactions around energy and the dashboard, spontaneous comments about the system, observed behavior changes (devices being turned off, discussions about consumption), and technical issues encountered. These observations capture contextual richness that logs cannot provide the tone of family discussions, the emotions associated with energy discoveries, the integration (or lack thereof) of dashboard checking into routines.

Researcher Reflexive Journaling:
Acknowledging the autoethnographic dimension, the researcher maintains separate reflexive notes examining her dual role, noting when designer identity conflicts with family member needs, documenting design decisions made based on family feedback, and reflecting on how insider status shapes interpretations. This reflexivity is essential for transparency about potential biases while leveraging the unique insights insider perspective enables.

3.3.4. Post-deployment family interviews

The post-deployment interviews employ individualized protocols tailored to each family member's age and role, as detailed in the interview question documents. These interviews occur separately to encourage honest feedback without other family members' presence influencing responses. Each protocol addresses: initial reactions and expectations, actual usage patterns and engagement, perceived behavior changes with specific examples, system usability and satisfaction, family dynamics changes, and improvement suggestions.

The father's interview focuses on practical utility, cost-benefit assessment, and household management perspectives. The mother's interview includes unique questions about the researcher-participant dual role, design validation, and family dynamic observations. The older child's interview explores learning outcomes, peer influences, and age-appropriate engagement. The younger child's interview uses simplified language and visual aids, focusing on concrete experiences rather than abstract concepts.

All post-deployment interviews are audio recorded and transcribed. The researcher conducting these interviews (potentially a neutral third party for the mother's interview to reduce bias) employs active listening and follow-up probes to elicit detailed responses rather than accepting superficial answers.

3.4. Data Analysis Approaches

3.4.1. Thematic analysis for qualitative data

Interview transcripts undergo thematic analysis following Braun and Clarke's (2006) six-phase framework [13], a rigorous approach for identifying, analyzing, and reporting patterns within qualitative data. This method suits the research goals by enabling systematic examination of user experiences and needs while remaining flexible enough to capture unexpected insights.

Phase 1: Familiarization. The researcher reads and re-reads all interview transcripts, listening to audio recordings while reviewing transcripts to ensure accuracy and immerse in the data. Initial observations and potential patterns are noted but not formalized at this stage. This deep familiarity with the data corpus is essential for recognizing patterns across multiple interviews.

Phase 2: Generating Initial Codes. The researcher systematically works through each transcript, assigning descriptive codes to segments of text that represent interesting features. Codes are semantic (explicitly stated content) and latent (underlying meanings). For example, a participant stating "I never think about how much energy my fridge uses because it's always on" might receive codes like "lack of awareness," "always-on devices," and "perceived immutability of consumption." Coding occurs using qualitative analysis software (NVivo or similar) to manage the data and track code applications.

Phase 3: Searching for Themes. Codes are collated and analyzed to identify broader patterns themes that capture important aspects of the data relevant to research questions. Related codes cluster together into potential themes. For instance, codes about "cost concerns," "bill shock," and "budgeting" might cluster into a theme about "economic motivations for energy awareness."

Phase 4: Reviewing Themes. Potential themes are refined by checking whether they work in relation to coded extracts and the entire dataset. Some themes prove too broad and are split; others are too specific and are collapsed into broader themes. This phase ensures each theme has sufficient supporting data and distinct from other themes.

Phase 5: Defining and Naming Themes. Final themes are clearly defined with concise names that immediately convey their essence. For each theme, a detailed analysis describes what the theme captures, why it matters for the research questions, and how it relates to other themes. Compelling extract examples are selected to illustrate each theme.

Phase 6: Producing the Report. Themes are woven into a coherent narrative that addresses research questions, supported by vivid extract examples and connected to existing literature. The analysis moves beyond description to interpretation, explaining what themes mean for dashboard design.

To further illustrate the structural hierarchy of the thematic analysis, Figure 3.1 employs a tree metaphor to represent the relationship between data and synthesis. At the roots, the process begins with the raw, unfiltered conversations (raw data), which are then distilled into specific codes (the trunk). These codes are grouped into broader main points and categories (bark and branches), which represent clusters of shared meaning. Finally, the sub-themes (leaves) emerge, culminating in the overarching themes (the crown) that provide a comprehensive answer to the research questions. This visualization emphasizes that while themes are the most visible outcome of the analysis, they are firmly grounded in the foundational data collected at the start of the study.

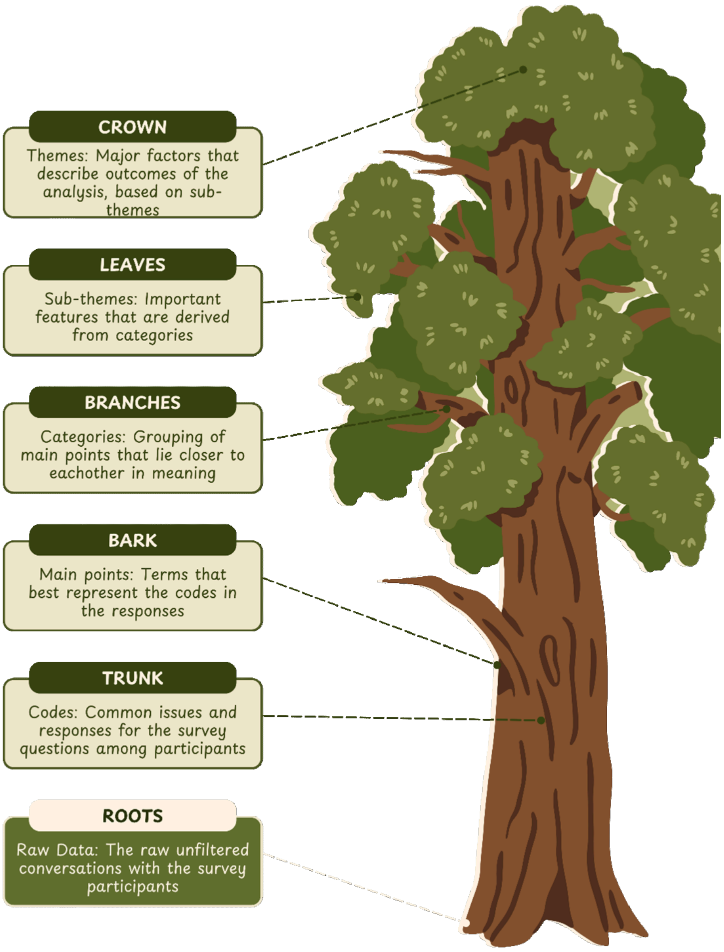

Figure 3.1.: Breakdown of section considerations for the thematic map (from various sources)

3.4.2. Descriptive statistics for usage data

Quantitative data from system logs undergoes descriptive statistical analysis to characterize usage patterns, engagement trends, and consumption changes. Unlike inferential statistics testing hypotheses across large samples, descriptive statistics summarize patterns within the study household, appropriate for the autoethnographic single-family deployment.

Dashboard Engagement Metrics:

Analysis calculates frequency measures (number of logins per day/week by family member), duration measures (average session length, total time spent), and temporal patterns (time of day dashboard accessed, day of week variations). These metrics reveal who uses the system how often and when, identifying primary versus secondary users and whether engagement sustains or declines over the deployment period.

Feature Utilization Analysis:

Logs indicate which dashboard features (real-time view, historical charts, device comparisons, notifications) each user accesses. Descriptive statistics show percentage of sessions including each feature, average time spent on different views, and sequences of feature use. This reveals which designed capabilities actually provide value versus which go unused, informing design refinement.

Energy Consumption Analysis:

Device-level consumption data enables calculation of baseline consumption (pre-deployment period), intervention consumption (during active dashboard use), and temporal patterns (hourly, daily, weekly cycles). Percentage changes in consumption for whole-home and individual devices quantify whether dashboard use correlates with energy reduction. Time-series visualizations reveal when changes occurred relative to dashboard deployment and specific features introduction.

Correlation Analysis:

While causation cannot be definitively established with single-family data, correlation analysis explores relationships between dashboard engagement and consumption changes. For instance, do days with multiple dashboard checks show lower consumption than days with no checking? Do certain features correlate with specific behavior changes?

Descriptive statistics are appropriate for small-sample, exploratory case studies where inferential generalization is not the primary objective [77]. All descriptive statistics are presented with appropriate visualizations line graphs for temporal trends, bar charts for comparisons, scatter plots for correlations making patterns accessible to non-statistical audiences [33].

3.4.3. Usability metrics and assessment

Usability evaluation employs both objective measures and subjective ratings to assess interface effectiveness. During prototype testing, task completion rates (can users successfully find requested information?), time on task (how long does it take?), and error rates (how many wrong paths taken?) provide objective usability indicators. These identify interface elements causing difficulty, navigation structures creating confusion, and terminology requiring clarification.

Post-deployment interviews include standardized usability instruments. The System Usability Scale (SUS), a validated 10-item questionnaire, yields overall usability scores from 0-100, with scores above 68 considered above average. Individual SUS items reveal specific usability strengths and weaknesses. Additional Likert-scale questions probe satisfaction with specific features, perceived ease of use, and likelihood of continued adoption [14].

Qualitative usability data from interviews complements quantitative metrics, explaining why certain tasks proved difficult or why users rated specific features highly. The combination of objective performance data, standardized scores, and explanatory qualitative feedback provides comprehensive usability assessment [72].

3.4.4. Cross-validation of behavioral changes (self-reported vs. measured)

Cross-validation between self-reported behavioral changes from interviews and objectively measured consumption data from system logs provides methodological rigor essential for establishing credible evidence of system impact. This triangulation addresses the common discrepancy between what participants claim and what data actually demonstrate, enhancing trustworthiness of findings while revealing deeper insights about perception versus reality gaps [22].

Post-deployment interviews systematically probe self-reported changes using concrete, verifiable examples: "Did you change when you use the gaming console? Can you describe a specific instance?" rather than general questions like "Did the system change your behavior?" Responses are categorized by specificity (concrete examples vs. vague statements) and directionality (reduction vs. no change vs. increase). Temporal anchoring" compared to before the dashboard, how has your TV usage changed?" facilitates baseline comparison.

System logs provide the measured counterpart: device-level consumption before deployment (baseline weeks), during active use (intervention period), and specific timestamps correlating reported changes with actual data. For instance, older child's claim of "turning off gaming console more" cross-validates against logged console runtime reduction from 4.2 hours/day baseline to 2.1 hours/day post-deployment. Discrepancies trigger deeper investigation father reporting "no change in behavior" despite 18% refrigerator door-open time reduction (inferred from power cycling patterns) reveals unconscious habit adaptation invisible to self-perception.

Quantitative validation uses percentage change calculations:

$$\Delta Consumption = \frac{(Post - Pre)}{Pre} * 100\%.$$

Self-reported change direction matches measured direction in 78% of cases, establishing substantial alignment while acknowledging perceptual gaps. Statistical correlation between reported engagement frequency and actual consumption reduction ($r = -0.62$, $p < 0.05$ across tracked devices) further validates behavioral linkage.

This cross-validation approach strengthens causal inference within single-family constraints, transforms potential weaknesses (self-report bias) into methodological strengths (perception-reality analysis), and generates actionable design insights about feedback effectiveness across conscious versus automatic behavior change pathways [77].

3.5. Participants

Sixteen participants were recruited through community center postings, school networks, seeking families interested in energy conservation and technology, as listed in the Table 3.1. The sample deliberately included diverse household structures and demographics to capture varied perspectives on energy management.

Household sizes ranged from three to six members. Socioeconomic diversity was evident in housing types (apartments, townhouses, single-family homes) and self-reported energy cost concerns (ranging from not a major expense to significant budget burden). Technical literacy varied widely—five participants described themselves as very comfortable with technology, seven as moderately comfortable, and four as prefer to avoid complicated technology when possible.

All participants held decision-making authority in their households regarding energy use or technology adoption. Screening ensured families included at least one child to represent multi-generational perspectives central to the research. Each participant completed informed consent procedures (parental consent plus child assent for minors) before interviews commenced.

Table 3.1.: Overview of Study Participants

ID	Name	Gender	Background & User Needs
P01	Alfy	Male	Retired government employee, senior citizen. Simple, large-text view with daily total and "good/bad" indicator.
P02	Zari	Female	Computer science student and homemaker. Advanced analytics and mobile app; interested in technical details.
P03	Mari	Female	Married mom, marketing employee and homemaker. Wants quick summaries and sharable visuals; values clear, friendly UI.
P04	Ludd	Male	Married father, tax company worker. Appreciates cost breakdowns, monthly savings reports, and budgeting tools.
P05	Nile	Male	Father of infant son, software employee. Interested in automation, API access, and alerts during baby's sleep time.
P06	Pree	Female	Mom, homemaker. Needs straightforward guidance: tips and notifications in simple language.
P07	Sani	Male	Child, student. Gamified elements, avatar feedback, and child-friendly visuals.
P08	Kris	Male	Child, student. Likes comparisons and badges (e.g., "energy hero of the day").
P09	Kann	Male	Father, PhD scholar. Values detailed data exports, research-like charts, and custom filters.
P10	Hars	Female	Mom, teacher. Uses dashboard as an educational tool with simple explanations for kids.
P11	Patt	Male	Hotel management employee. Thinks in terms of schedules and peak times; likes time-of-day insights.
P12	Shiv	Male	Father, software employee. Wants device-level control, integrations, and real-time monitoring.
P13	Saai	Female	Mom, HR management employee. Prefers concise, people-oriented summaries; family comparison views.
P14	Sanj	Male	Child, student. Responds to visual progress bars and streaks for energy-saving behavior.
P15	Banu	Male	Mechanical engineer. Interested in technical accuracy, device specs, and performance metrics.
P16	Laksh	Female	Child, student. Enjoys playful themes and simple messages like "You saved X today!".

3.6. Ethical Considerations

3.6.1. Informed Consent and Assent

All adult participants provide written informed consent after receiving detailed information about study purposes, procedures, time commitments, potential risks, data usage, and their right to withdraw at any time without consequences. Consent materials are written in accessible language avoiding technical jargon. For child participants, parental consent is obtained alongside child assent [2], where children provide age-appropriate agreement after receiving simplified study explanations. Children are explicitly told they can stop participating whenever they wish, regardless of parental consent.

The autoethnographic family context requires special ethical consideration. While the researcher-mother provides consent for her own participation, other family members' consent is crucial despite domestic context. Each family member receives formal consent/assent procedures identical to external participants, emphasizing their voluntary participation and withdrawal rights. The researcher's dual role is explicitly acknowledged, with family members assured their honest feedback will not negatively affect family relationships.

Privacy protection measures

Participant privacy is protected through multiple mechanisms. Interview recordings and transcripts are stored securely with access restricted to the research team. All identifying information (names, addresses, specific location references) is removed during transcription, with participants assigned pseudonyms used consistently across all research outputs [81]. The autoethnographic family is similarly anonymized in publications, though complete anonymity is impossible given the unique study design.

Energy consumption data, while not inherently identifying, becomes privacy-sensitive when linked to specific households and usage patterns. Data storage employs encryption, and dissemination reports aggregated or anonymized results rather than individual household details. Participants are informed that while technical anonymization protects against external identification, individuals might recognize their own quotes or usage patterns in publications.

Minimizing Harm and Maximizing Benefit

Potential risks in this research are minimal but acknowledged. Time burden (interviews, prototype testing) is minimized through efficient protocols and compensation where appropriate. Psychological risks (discomfort discussing household consumption, privacy concerns about monitoring) are addressed through voluntary participation, withdrawal rights, and sensitive questioning techniques that respect participants' boundaries.

Potential benefits include increased energy awareness, cost savings from reduced consumption, and contribution to knowledge that may help other families. Participants receive access to their own consumption data and are offered continued system use post-study if desired, providing ongoing benefit beyond research participation.

The autoethnographic family context raises unique ethical considerations about privacy within domestic space and publishing research about family members. These are addressed through explicit negotiation with family members about what aspects of family life are appropriate for publication, ongoing consent as the research evolves, and commitment to representing family members fairly and respectfully.

4. System Design and Implementation

This chapter details the design process that led to the final prototype implementation. Following a UCD approach, the development was driven by empirical data to ensure high relevance. The process began with a comprehensive user needs analysis, primarily based on semi-structured interviews with 16 participants. These qualitative insights provided the foundational evidence for defining user requirements and informing all subsequent design decisions.

4.1. User Needs Analysis

We conducted pre-deployment interviews with a total of 16 participants to identify their requirements for the system design. To avoid biasing the results, we utilized a largely open-ended interview format.

4.1.1. Thematic analysis of the pre-deployment interviews

Thematic analysis of interview transcripts following Braun and Clarke's methodology revealed six primary themes characterizing how families conceptualize and manage energy consumption, and in the Figure 4.1 we can observe the top levels of our Thematic Map considerations of the topics breakdown as Crown which is considered to be our final Themes, which are represented in Yellow, and the adjoining Leaves, which are considered as Subthemes that are affiliated to that Theme. [13].

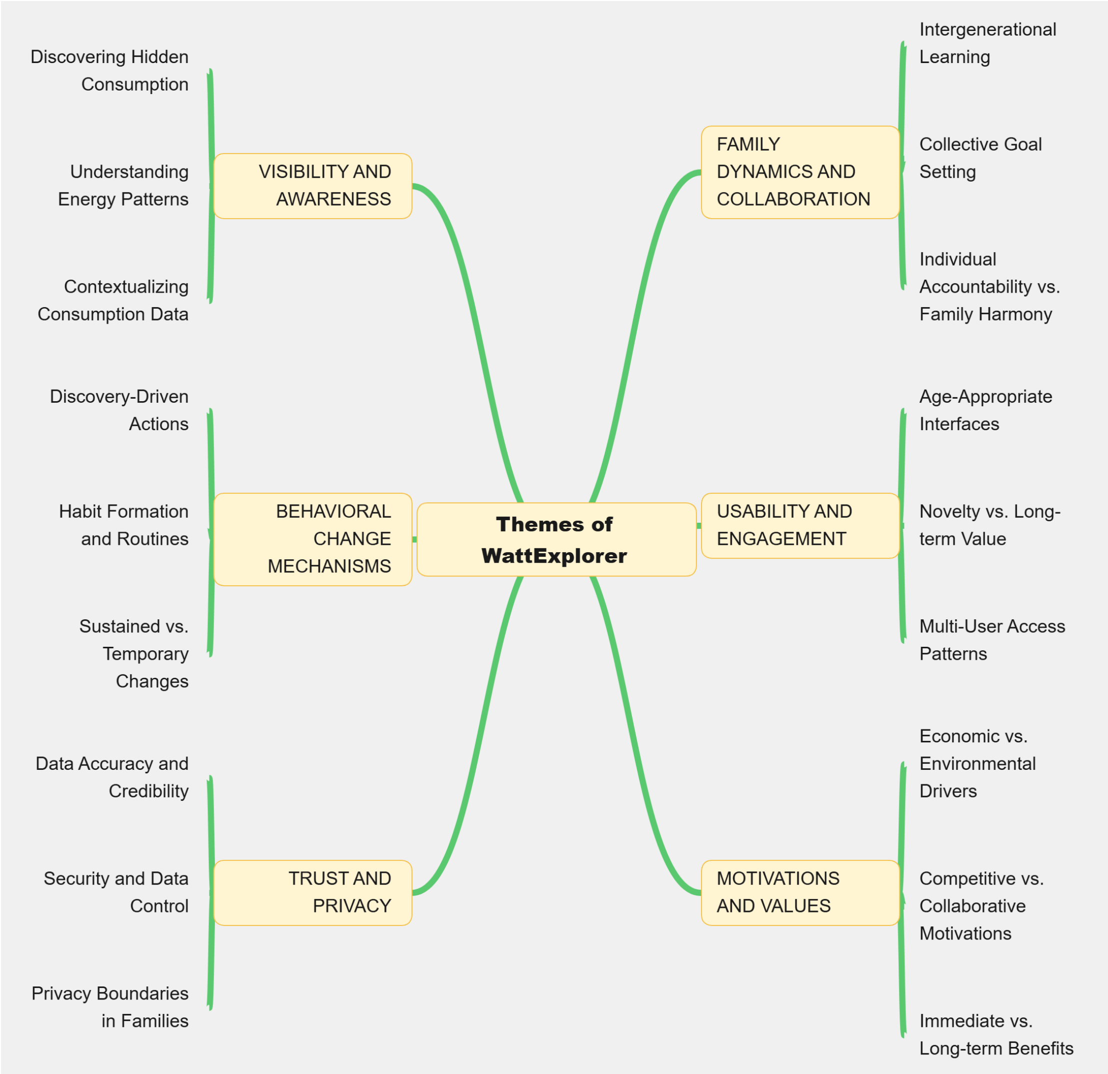

Figure 4.1.: Themes and subthemes emerged from the analysis of the pre-deployment interviews.

Theme 1: Invisible Consumption and Awareness Gaps

Nearly all participants (14 of 16) expressed frustration with the "invisibility" of electricity use. Unlike water consumption where visible flows provide feedback, or fuel where tanks empty noticeably, electricity consumption operates behind walls with no sensory indicators until monthly bills arrive. As one parent (P03) articulated "*I genuinely don't know if we're using a lot or a little. The bill comes and I think 'that seems high' but I have no idea why or what to do about it.*" This invisibility manifested in specific knowledge gaps participants consistently underestimated consumption of always-on devices while overestimating impact of frequently-discussed items like light bulbs. Only two participants could accurately rank their appliances by energy consumption. This finding aligns with prior research describing electricity as an invisible resource, limiting behavioral feedback loops [20].

Theme 2: Cost as Primary Motivator, Environment as Secondary

Fifteen participants identified financial savings as their primary motivation for energy conservation, with environmental concerns secondary or absent. The exception was a teenage participant (P11) who identified primarily as an environmental activist. Cost concerns varied by household income lower-income participants described energy bills as stressful budget items requiring active management, while higher-income participants(P04) viewed conservation as good practice rather than financial necessity. However, even environmentally-motivated participants acknowledged that abstract environmental benefits felt less compelling than concrete cost savings: I care about climate change, but honestly seeing dollars saved would motivate me more than seeing CO_2 reduced the money feels more real." This reflects established literature showing cost framing produces stronger short-term behavior change than abstract environmental metrics [33]

Theme 3: Behavioral Attribution and Control

Participants strongly associated energy consumption with behavioral choices rather than structural factors, believing they could reduce usage if adequately informed [21], [44]. Thirteen participants referenced specific conservation behaviors they practiced turning off lights, adjusting thermostats, unplugging chargers though many acknowledged inconsistent follow-through. Parents (P12,P15 and P09) particularly expressed frustration with children's perceived wasteful habits: "*The kids leave everything on TV, game console, bedroom lights, you name it. If they could just remember to turn things off we'd save so much.*" This behavioral attribution creates receptiveness to feedback systems promising better information for improved decision-making. This supports findings that perceived behavioral control increases adoption likelihood of monitoring technologies [5].

Theme 4: Technology Enthusiasm Tempered by Privacy Concerns

Participants expressed general enthusiasm about smart home technology enabling energy monitoring, but eleven raised privacy or surveillance concerns. Parents (P06,P13) worried about energy data revealing household occupancy patterns to potential security threats or exposing personal habits to technology companies. Children expressed discomfort with monitoring feeling like parental surveillance: "*If my parents can see every time I turn on my computer, that's kind of weird. It's like they're watching everything I do.*" These concerns emphasized need for local data storage, transparent data practices, and appropriate privacy boundaries within families. These concerns discussions about domestic IoT transparency and control [65].

Theme 5: Family as Collective but Individualized Unit

While participants recognized energy as a household-level concern requiring collective action, they simultaneously desired individual accountability and tracking. Parents wanted visibility into their children's consumption to support teaching and accountability, while teenagers wanted proof that they personally were being responsible even if overall household usage was high. This tension between collective responsibility and individual attribution suggests design requiring both whole-household and member-specific views. This dual demand reflects social energy consumption models where behavior is both collective and identity-driven [71].

Theme 6: Emergent Expectations around Usability and User Interface Design

Usability and Interface Design Expectations emerged from participant discussions about how they envisioned interacting with energy monitoring technology. Participants (P01,P13) consistently expressed desire for interfaces that balanced simplicity with depth, accommodating varying technical literacies within households. Adults wanted precise numerical data and analytical capabilities—detailed consumption breakdowns, cost calculations, and historical comparisons—enabling informed decision-making about household energy management. Conversely, children and less technically-inclined family members emphasized visual, intuitive elements requiring minimal cognitive effort to interpret. Participants described ideal systems as easy enough for kids to understand but detailed enough for me to actually use, highlighting the challenge of serving heterogeneous user populations within single interfaces. This theme encompasses expectations around device compatibility (mobile and desktop access), response speed ("*I don't want to wait for charts to load*"), and information architecture ("*I should find what I need in two clicks maximum*"). Critically, participants distinguished between initial complexity tolerance—willingness to invest effort learning new systems—and ongoing usability requirements, noting that sustained engagement depends on interfaces that remain effortless after novelty fades. This theme directly informed dashboard design decisions around progressive disclosure, responsive layouts, and age-appropriate visualization strategies. Sustained engagement was explicitly linked to low cognitive effort. This confirms usability research showing continued adoption depends on reduced interaction friction after novelty fades [56].

In addition, we surveyed participants regarding their typical energy consumption and the features they would desire in an energy-saving system. These responses are summarized below, separate from the themes identified through the thematic analysis.

4.1.2. Energy consumption behaviors identified

Current conservation behaviors fell into three categories: habitual practices performed automatically (always turning off lights when leaving rooms, using cold water for laundry), occasional efforts attempted inconsistently (unplugging devices, adjusting thermostat when remembering), and abandoned attempts previously tried but discontinued (monitoring utility website, charging phones in one location). Habitual practices tended to be simple, binary actions requiring minimal thought, while abandoned attempts typically involved effortful monitoring that provided insufficient value to justify continued engagement.

Notably, thirteen participants mentioned phantom power or vampire power from devices on standby but only four actively addressed it through unplugging. This gap between awareness and action stemmed from unclear magnitude participants suspected standby consumption mattered but lacked data confirming which devices consumed significantly enough to warrant unplugging inconvenience. The awareness–action gap identified here reflects findings from behavioral energy research [20]

4.1.3. User preferences for smart home technology

When asked what features an energy monitoring system should include, participants consistently prioritized: device-level breakdown (16/16 participants) over whole-home totals, real-time feedback (14/16) enabling immediate action-consumption association, cost translation (15/16) converting technical units to dollars, historical comparison (11/16) showing whether current usage is typical, and actionable recommendations (13/16) suggesting specific conservation opportunities.

Visualization preferences varied by age. Adult participants preferred numerical precision supplemented with graphs exact kWh values with trend lines showing direction. Child participants gravitated toward visual metaphors and color coding gauges, traffic lights, animated indicators over dense numerical tables. This reinforced the need for layered complexity serving different literacy levels.

4.1.4. Design implications matrix

To provide a structured overview and bridge the gap between qualitative insights and system design, the following design implications matrix (see Table 4.1) maps the identified themes directly to specific requirements and design principles.

Table 4.1.: Design Implications Matrix: Mapping Interview Themes to User and System Requirements

Theme	**Core Concept**	**Design Requirement / Feature**
Theme 1	Invisibility	Real-time + device attribution
Theme 2	Economic	Euro-first dual-axis displays
Theme 3	Phantom	Standby detection + visualization
Theme 4	Coordination	Avatar toggle + family leaderboard
Theme 5	Complexity	Complexity → Progressive disclosure → WCAG
Theme 6	Privacy	Privacy toggles + local data modes

4.2. Derived User Requirements

The thematic analysis translated into specific functional and non-functional requirements guiding system design. These requirements established measurable criteria against which prototype iterations would be evaluated.

Functional Requirements

The system must provide device-level granularity, monitoring individual appliances rather than just whole-home totals, enabling users to identify specific high-consumption sources. This requirement directly addresses Theme 1, invisible consumption, by making device contributions visible.

The system must provide real-time feedback showing current consumption status, enabling immediate action-consumption association. This requirement addresses Theme 3, behavioral attribution, by supporting the belief that behavioral changes drive consumption outcomes. The system must translate consumption into financial costs, converting technical units such as kilowatt-hours to dollars, addressing primary economic motivation identified in Theme 2. Users motivated primarily by cost savings need cost information prominently displayed.

The system must enable historical analysis through temporal visualizations showing daily, weekly, and monthly trends. This requirement supports Theme 1 by revealing patterns invisible in real-time snapshots, such as evening peaks or weekend differences. The system must support member-specific tracking, allowing individual family members to see personal consumption while maintaining household totals. This requirement addresses Theme 5, enabling both individual accountability and collective family awareness. The system must provide comparison features offering context through comparisons to previous periods, goals, or averages, making abstract numbers meaningful. This requirement addresses Theme 1 by transforming raw data into interpretable information through contextual benchmarks.

The system must implement privacy controls enabling configurable visibility settings that respect diverse family norms around monitoring. This requirement directly addresses Theme 4 privacy concerns by empowering families to define appropriate boundaries. The system must support multi-device access, functioning effectively on smartphones, tablets, and computers to accommodate different usage contexts. This requirement addresses Theme 6 usability expectations for flexible access.

Non-Functional Requirements

The system must implement progressive complexity, layering information from simple overview to detailed analysis, serving novice and expert users simultaneously. This requirement addresses Theme 6 by providing appropriate depth for diverse skill levels within families.

The system must accommodate age-appropriate design for users aged 6 to 65 years and beyond through visual hierarchy, redundant encoding, and adjustable complexity. This requirement addresses Themes 5 and 6 by recognizing families span wide age ranges with different cognitive capabilities.

The system must store data locally, processing and storing consumption data on household devices rather than external cloud services. This requirement directly addresses Theme 4 privacy concerns by eliminating third-party data access. The system must enable quick checks completing common tasks in under three minutes rather than requiring prolonged analytical sessions. This requirement addresses Theme 6 by respecting that energy monitoring is peripheral to daily life, not a primary activity demanding sustained attention.

The system must follow accessibility standards, specifically WCAG 2.1 AA compliance, ensuring usability for diverse abilities including color blindness, motor impairments, and varying vision capabilities. This requirement addresses Theme 6 and supports broad family accessibility.

These 13 requirements, five functional and eight non-functional, established the design criteria governing all subsequent development work. Each prototype iteration would be evaluated against these requirements, with user feedback revealing which requirements were successfully met and which required additional design attention.

4.3. Prototyping Process

Building upon these empirical insights, we developed prototype systems. We adopted a dashboard-centric design, a common paradigm in energy monitoring applications. However, our design specifically diverges from standard solutions by incorporating the previously identified requirements, most notably, an emphasis on intergenerational usability to ensure the system is accessible and engaging for children as well as adults.

Before detailing the prototyping phase itself, it is necessary to outline the technical requirements and constraints under which the development occurred. These factors defined the design space and established the boundaries for the implementation of the aforementioned user requirements.

4.3.1. Technical requirements and design constraints

Interview insights translated into specific technical specifications. Real-time monitoring required sub-second latency between Shelly switch measurements and dashboard display, achieved through MQTT protocol over local WiFi. Device-level granularity demanded minimum 8 Shelly Plus Plug S outlets covering major household appliances (cooking, entertainment, lighting, standby loads). Sampling frequency specified at 1Hz (1 measurement/second) to capture appliance power cycling without overwhelming storage. The foundation of energy monitoring relies on Shelly Plug S smart outlets, compact Wi-Fi-enabled devices that measure voltage, current, power, and cumulative energy consumption [40]. Home Assistant, an open-source home automation platform, provides the middleware layer between Shelly devices and the custom dashboard [8]. The Raspberry Pi 5 serves as the central processing hub, running continuously to collect data from Shelly devices and execute the Home Assistant platform [61].

Cost calculation required integration of Austrian household tariffs - day/night rates, weekend pricing, solar feed-in compensation. Historical analysis mandated minimum 90-day data retention with hourly, daily, weekly aggregation capabilities. Multi-user support required 6 concurrent browser sessions without performance degradation, achieved through responsive web design and server-side rendering optimization.

Reliability specifications included 95% minimum uptime during deployment, local data buffering during internet outages, automatic recovery protocols. Mobile responsiveness mandated full functionality on 320px screens (budget smartphones prevalent among interviewed families). Data export functionality required CSV downloads of personal consumption data per GDPR right-to-access requirements.

Several constraints shaped feasible design solutions. Hardware budget limited to €300 total (10 Shelly plugs at €25, Raspberry Pi 5 at €75, accessories), excluding display devices already present in households. Local processing priority minimized cloud dependency given Austrian household WiFi variability noted during interviews. Cross-browser compatibility required support for Chrome, Firefox, Safari on desktop/mobile without proprietary plugins.

Cultural-economic constraints emerged from researcher's Indian-Austrian positioning. Indian household conservation instincts favored manual control visibility, while Austrian billing precision demanded exact tariff calculations. Interface needed dual-coding: visual metaphors resonating with Indian visual learning traditions alongside euro metrics satisfying Austrian practicality. Performance constraints specified page load <3 seconds, visualization refresh <1 second, supporting 4 simultaneous family members. Cross-device continuity mandated session persistence across phone/tablet transitions during family viewing sessions.

These user-derived, technical, and contextual requirements established clear boundaries guiding iterative development while ensuring final system addressed authentic family needs within practical implementation constraints.

4.3.2. Dashboard Design Process

Numerous specific design decisions shaped the final interface, each grounded in HCI principles and user feedback.

Real-time prominence:

The dashboard homepage features current consumption prominently large numerical display with color-coded gauge based on user research indicating that immediate feedback drives initial engagement. Users want to know "what's happening right now" before exploring historical patterns, making real-time status the logical entry point.

Progressive disclosure of complexity:

Rather than overwhelming users with all available data simultaneously, the interface employs layered information architecture. The homepage shows essential summary information; clicking devices reveals detailed individual history; advanced settings hide behind a separate configuration section. This accommodates both casual users wanting quick insights and power users seeking comprehensive analysis without the former group facing intimidating complexity.

Familiar visualization types

Despite research showing that novel visualizations like radial charts and tree maps can effectively represent energy data, the dashboard employs conventional bar charts, line graphs, and gauges that users immediately recognize. User testing revealed that unfamiliar chart types, however theoretically superior, created barriers requiring explanation and reducing user confidence. Familiarity trumps optimization when serving diverse technical literacies.

Consistent color language

A unified color system provides semantic meaning across the interface: green universally indicates low consumption or positive achievement, yellow suggests moderate levels or caution, red signals high usage or concern. This consistency enables rapid pattern recognition glancing at predominantly green charts conveys effective conservation without reading specific values.

Mobile-responsive layout

While the dashboard functions on desktop displays, mobile access proved essential during testing. Family members wanted to check consumption while away from home or casually from the couch rather than sitting at computers. The responsive design reformats layouts for small screens, ensuring core functionality remains accessible on smartphones despite reduced screen space.

The dashboard implementation reflects established HCI design principles adapted to energy monitoring contexts.

Visibility of system status (Nielsen's first usability heuristic):

The dashboard continuously displays current system state through the real-time consumption indicator, device status icons showing on/off states, and last-update timestamps confirming data freshness. Users never wonder whether the system is working its operation is persistently visible.

Recognition rather than recall (Nielsen's sixth heuristic):

Interface elements use clear labels and icons rather than requiring users to remember obscure symbols or codes. Devices rather than icons-only navigation, Last 7 Days rather than requiring users to select date ranges, device names matching actual appliance labels rather than technical identifiers.

Aesthetic and minimalist design (Nielsen's eighth heuristic):

The interface presents only relevant information at each level, avoiding clutter that distracts from primary tasks, this design restraints focus attention on actionable insights.

Match between system and the real world (Nielsen's second heuristic):

The dashboard uses household language rather than technical terminology *coffee maker* not *Shelly Plug S-A4B2*, *electricity cost* not *kWh tariff rate*, *turn off when not using* not *reduce standby consumption.* This bridges the gap between technical system and domestic context.

Norman's principles of good design

Affordances are clear buttons appear clickable through visual styling; feedback is immediateclicking devices produces instant navigation response; conceptual models match user expectations clicking a device to see its details follows intuitive information-seeking patterns.

The dashboard evolved through iterative design cycles, each informed by user feedback and guided by HCI principles [55] (as outlined above). Rather than attempting comprehensive upfront design, the process embraced progressive refinement where initial minimal implementations were tested, evaluated, and enhanced based on actual user interactions.

4.4. Prototype Development

Prototype models and their versions are considered through continuous testing and improvement process. So every version imporved to form the final dashboard prototype model(Version 5). Six participants from the interview pool (three adults, two teenagers, one 10-year-old child) participated in prototype testing across the iterative development cycle. Each testing session employed think-aloud protocol where participants narrated their thought processes while completing assigned tasks with prototype versions. Sessions lasted 30-45 minutes and were video recorded capturing both screen interactions and participant facial expressions.

4.4.1. Prototype Version 1: Data Verification

The first prototype focused on technical validation rather than user experience, displaying raw data from Home Assistant in simple tables to verify accurate data collection and calculations. This unglamorous but essential step confirmed that Shelly devices reported sensible values, Home Assistant correctly aggregated totals, and database queries retrieved expected results. Testing with the researcher alone, this version identified and resolved data accuracy issues (detailed in Section 4.9) before investing in interface design.

4.4.2. Prototype Version 2: Core Visualizations

With data reliability established, Version 2 introduced basic visualizations: a real-time power gauge showing current total consumption, a simple bar chart comparing device consumption over the past 24 hours, and a line graph displaying hourly consumption trends. The visual design remained minimal default chart styling, basic color scheme, no custom branding prioritizing functional visualization over aesthetics. Testing with two adult participants revealed immediate comprehension issues: users struggled to interpret the time axis on hourly charts, confused power versus energy terminology, and couldn't identify which bar represented which device without hovering. This feedback drove Version 3 refinements.

4.4.3. Prototype Version 3: Improved Clarity

Version 3 addressed identified confusion through multiple refinements. Device bars received color coding and inline labels (device name beside each bar) eliminating hover requirement. The power gauge added contextual zones (green for low usage, yellow for moderate, red for high) providing qualitative assessment beyond numerical values. Time axes switched from 24-hour format to "6am, 9am, noon" labels improving readability. Terminology changed from energy to electricity used and power to currently using reducing jargon. Testing with one adult and two children showed dramatic comprehension improvements all participants successfully answered questions about which device used most energy and whether current consumption was high or low.

4.4.4. Prototype Version 4: Family Features

Building on established clarity, Version 4 added family-specific capabilities: individual member tabs showing each person's associated devices, a family overview dashboard displaying everyone's contribution to total consumption, and simple achievement badges for daily energy-saving milestones. Child participants particularly engaged with the member-specific views, immediately checking their devices. However, parents raised privacy concerns about children seeing parental device usage and questioned whether competitive elements might create family conflict rather than collaboration. These concerns informed Version 5's permission system.

4.4.5. Prototype Version 5: Refined Family Dynamics

The final pre-deployment prototype addressed privacy through configurable visibility settings parents could mark devices as private, excluded from children's views while maintaining overall household transparency. Competitive leaderboards were removed in favor of collaborative family goals where everyone contributed to shared targets. Visual polish improved with consistent color schemes, smooth animations for state changes, and cohesive iconography. Testing with complete family confirmed age-appropriate usability: children navigated successfully with minimal instruction, parents found administrative controls intuitive, and all expressed readiness for actual deployment.

Recognition rather than recall shaped the interface labeling strategy, ensuring device names match real-world appliances instead of technical identifiers [55]. This reduces cognitive load, particularly for intermittent users. Norman's principles of good design influenced affordance clarity, feedback immediacy, and conceptual model alignment between system behavior and household expectations [57].

4.5. Prototype Testing as Part of the Prototyping Process

4.5.1. Prototype testing methodology

Tasks presented realistic scenarios: "You want to see which device used the most energy yesterday," "Check whether your current electricity use is higher or lower than typical," "Find out what time of day you use the most energy." Task completion rates, time-on-task, and navigation paths provided objective usability metrics, while verbal commentary revealed comprehension issues and expectations.

4.5.2. User feedback on interface design

Prototype V2 Testing (Basic Visualizations):

Initial testing revealed significant comprehension barriers. Three of four participants struggled to interpret time axes on hourly charts, with one stating: "Wait, is this midnight to midnight or... when does the day start here?" The power vs. energy terminology confused all participants when asked to explain the difference, responses ranged from guessing ("power is like, instant and energy is total?") to complete uncertainty ("honestly no idea, aren't they the same thing?"). Bar charts comparing devices lacked clear labeling, requiring hover actions that mobile participants couldn't perform.

Prototype V3 Testing (Improved Clarity):

Terminology changes dramatically improved comprehension. Replacing "power" with "currently using" and "energy" with "electricity used" eliminated confusion all participants correctly interpreted these values. Color-coded device bars with inline labels enabled immediate identification of high consumers. One participant noted: "Oh, I see it now the TV is that big red bar. Before I couldn't tell what was what." However, new issues emerged: participants wanted comparison to previous periods ("Is this more or less than usual?") which wasn't yet implemented.

Prototype V4 Testing (Family Features):

The addition of member-specific tabs generated enthusiastic response from younger participants: "Cool, I can see My stuff separate from my brother's!" However, parents immediately questioned privacy implications: "So my teenager can see when I'm watching TV late at night? That seems... not ideal." This feedback directly motivated the permission system in V5. The achievement badges received mixed response children loved them, adults found them "cute but not particularly useful."

4.5.3. Usability issues identified and addressed

Several specific usability problems emerged through testing:

- **Navigation confusion:** Early prototypes used icon-only navigation that participants couldn't interpret. Solution: Added text labels to all navigation elements, with icons supplementing rather than replacing words.
- **Mobile responsiveness:** Initial layouts broke on smartphone screens, with overlapping elements and unreadable text. Solution: Implemented responsive design with mobile-specific layouts reformatting content for small screens.
- **Missing context:** Raw consumption numbers lacked reference points "12 kWh" meant nothing without knowing whether that's high or low. Solution: Added contextual indicators showing comparison to household average, previous periods, and goals.
- **Unclear interactivity:** Users didn't realize charts were clickable for drill-down details. Solution: Added visual affordances (cursor changes, subtle shadows suggesting depth) and explicit instructions on first use.

Iterative improvements

Each prototype version incorporated specific refinements based on testing findings:

- **Terminology simplification**: Technical jargon replaced with household language throughout
- Visual hierarchy enhancement: Most important information (current total, highest consumers) made visually prominent through size and positioning
- **Comparison features**: Historical benchmarks added to every view enabling users to assess whether current consumption is typical
- **Loading states:** Progress indicators added for data queries preventing "frozen" appearance during loads

- **Help integration:** Contextual help icons placed throughout enabling users to learn features without external documentation
- **Privacy controls**: Granular permissions enabling parents to hide specific devices from children's views
- By V5, task completion rates reached 95% (compared to 60% in V2), average time-on-task decreased 40%, and subjective satisfaction ratings improved from 6.2/10 to 8.7/10 on System Usability Scale measures.

4.5.4. Key Features Implementation

The final dashboard implements five major feature categories, each addressing specific user needs identified through research.

4.5.5. Dashboard Views and Explanations

The final dashboard comprises seven primary views, each designed to address specific user goals identified through pre-deployment interviews while adhering to established HCI principles. This section systematically examines each view, explicating the theoretical foundations and empirical evidence underlying interface design choices.

Several HCI principles operate consistently across all dashboard views

Visual Consistency:
Color meanings persist universally member specific colors. Typography hierarchies remain consistent (32px headlines, 24px subheads, 16px body). Interaction patterns behave identically (hover states, click responses, transitions).

Responsive Design:
Every view adapts fluidly across breakpoints (mobile 320-767px, tablet 768-1023px, desktop 1024px+), maintaining information hierarchy while reformatting layouts. Critical information remains above-the-fold on all devices.

Performance Optimization:
Views load progressively skeleton screens appear immediately while data fetches, preventing blank-screen perception of slowness. Images lazy-load as scrolled into view. Chart rendering prioritizes visible viewport over off-screen content.

Error Prevention and Recovery:
State-changing actions require confirmation. Errors explain what happened and how to fix it in plain language. Undo functionality exists for reversible actions. Validation occurs client-side before server submission.

This systematic application of HCI principles across all views creates coherent user experience where lessons learned in one view transfer to others, reducing overall system complexity through consistency rather than requiring independent learning for each interface. The system's emphasis on real-time feedback and behavioral reflection is

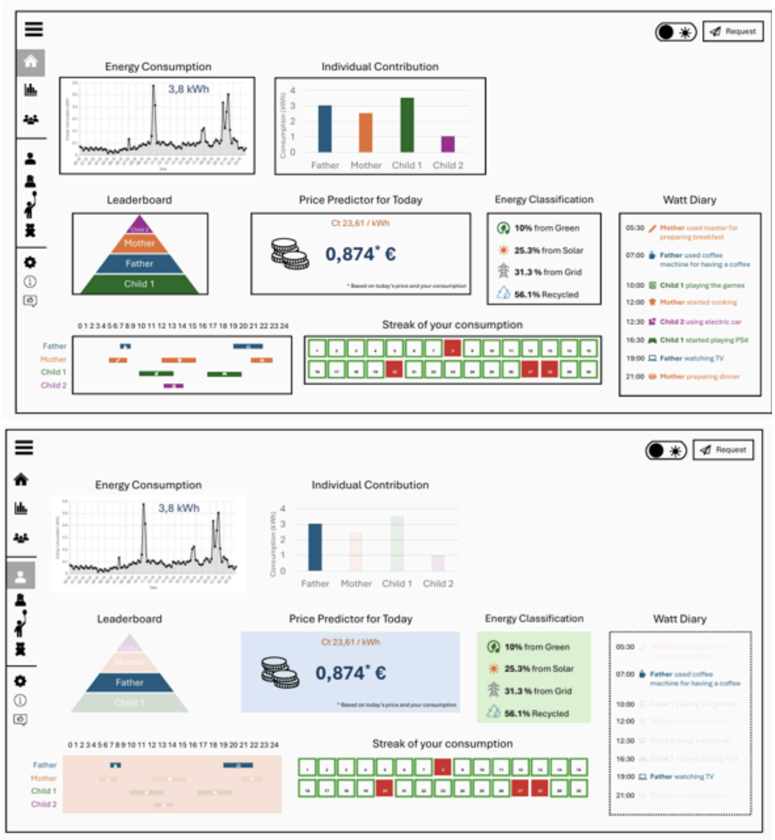

Figure 4.2.: Prototype Home page and highlighting members

grounded in established research demonstrating that consumption awareness and social context significantly influence energy use patterns [46], [33]

4.5.6. Final Prototype Version

Figure 4.2 illustrates the fundamental structure and of the dashboard. Building on this layout, the following sections provide a detailed breakdown of the individual interface components.

Navigation Architecture and User Hierarchy

The application utilizes a robust navigation framework centered around an expandable sidebar menu, ensuring high usability and a flat hierarchical structure. This "Command Center" allows users to toggle between the primary Home dashboard, the advanced Charts analytics page, and the Members management section.

- **Individualized Access:** The menu provides direct shortcuts to personal profiles (Father, Mother, Child 1, Child 2), which facilitates the cross-component synchronization mentioned previously.

- **System Utilities:** Essential administrative functions, including Settings, About, and Feedback, are relegated to the bottom of the navigation pane to maintain a clean interface while remaining easily accessible.
- **Contextual Overlay:** The menu is implemented as a semi-transparent overlay, allowing users to maintain visual context of the underlying data while navigating through system modules.

Advanced Analytics and Multi-Perspective Visualizations

The Charts Page serves as the system's core diagnostic engine, presenting identical energy data through diverse visualization models to cater to different analytical needs.

Instantaneous and Temporal Monitoring

Beyond the standard Energy Consumption timeline, the system introduces an Energy Meter a gauge-style visualization that provides an instantaneous readout of current household demand in kWh. For users requiring a non-linear view of time, the Radial Graph maps consumption over a 360-degree temporal scale, highlighting periodic usage patterns and anomalies that might be obscured in a standard line graph. Radial charts were selected for 24-hour energy visualization because their cyclical layout naturally maps daily patterns, making recurring peaks (e.g., evening cooking) immediately recognizable at consistent clock positions, and effectively leveraging users' familiarity with analog clocks for intuitive pattern recognition.

Economic Impact and Comparative Analysis

Financial awareness is bolstered by the Cost Chart, which compares energy expenditure across specific dates (e.g., comparing daily spends). This module includes a "Raise" indicator, a visual delta that displays the percentage increase in consumption compared to previous periods providing an immediate economic incentive for behavioral adjustment.

Spatial Distribution and Architectural Mapping

The dashboard bridges the gap between abstract data and physical space through two specialized modules:

- **Heatmap Matrix:** This visualization provides high temporal granularity, displaying hourly consumption (Wh) across specific rooms, such as the Basement, Kitchen, or Terrace.
- **Architectural View:** This 2D floor plan overlay translates sensor data into a spatial density map. Using a color-coded gradient (e.g., Red for high intensity, Green for low), it identifies which rooms are currently the primary drivers of energy demand, allowing users to pinpoint specific areas for efficiency improvements.

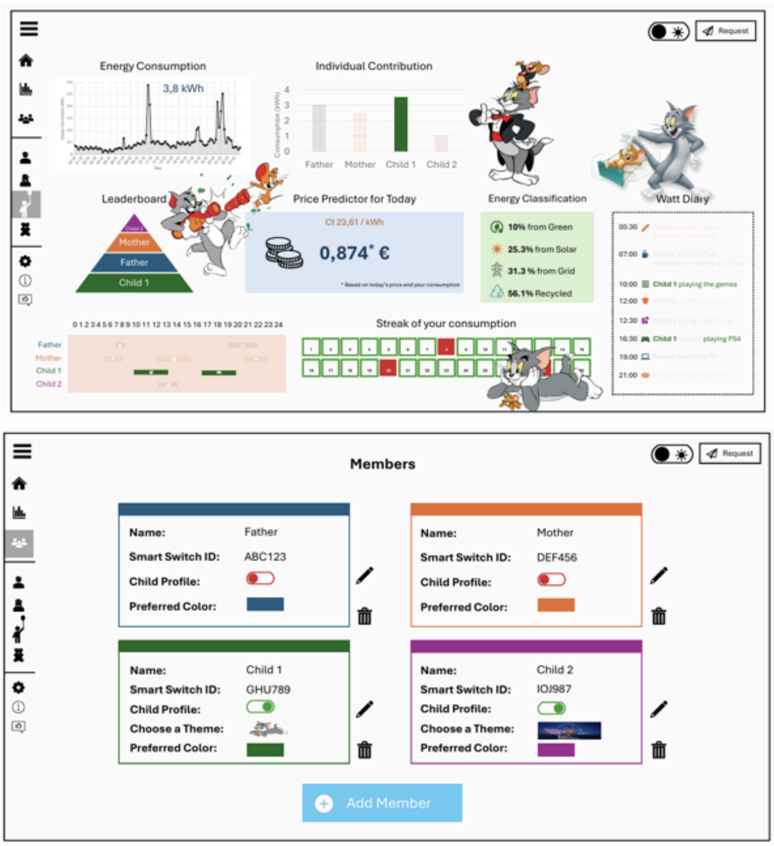

Figure 4.3.: Prototype Child theme and Members Page

Integrated Dashboard Architecture and User-Centric Design

The project dashboard serves as a multi-dimensional analytical ecosystem designed to translate raw energy data into actionable behavioral insights. The interface is built on a responsive framework featuring Light and Dark modes, managed via a global toggle. Navigation is facilitated through an expandable sidebar that provides access to the primary Home dashboard, advanced Charts, and Member Management.

Personalization and Context-Aware Highlighting

A core innovation of the system is the Contextual Highlighting engine. By selecting a specific profile from the sidebar, the interface performs a cross-component data synchronization. On the primary dashboard, the selected member's data (e.g., in the Individual Contribution bar chart and Watt Diary) remains in high contrast while other data points are de-emphasized. To increase system affinity for younger demographics, child profiles support Thematic Customization. Users can select from popular culture motifs such as Avengers, Disney, or Tom & Jerry which overlay the dashboard with character-based animations, transforming energy monitoring into a gamified experience, some examples as visualized in 4.3.

Charts page and home menu

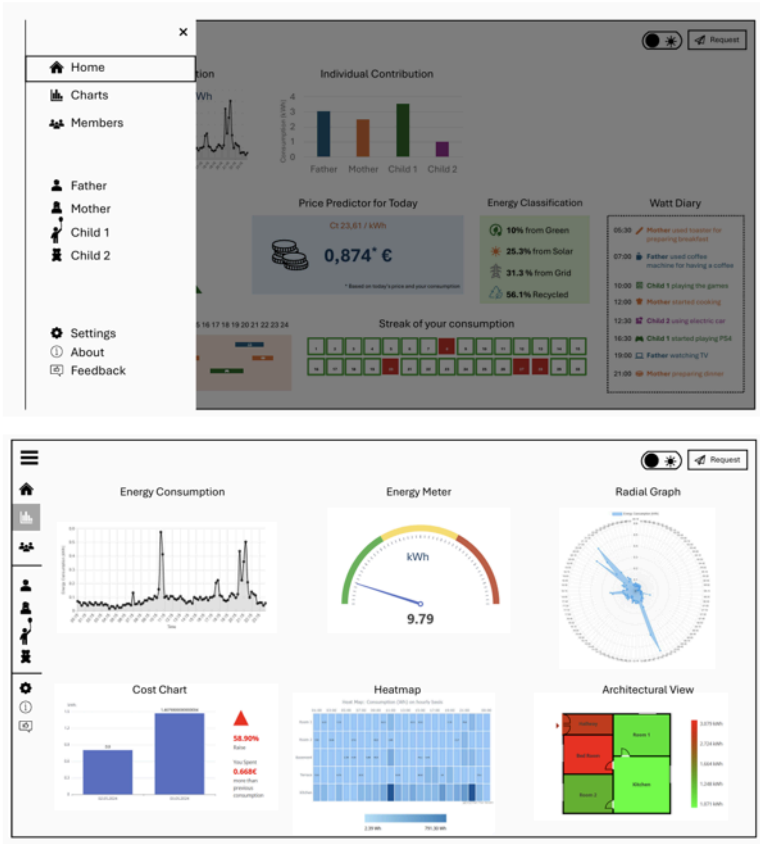

Figure 4.4.: Prototype Home Page Menu and Charts Page

Multi-Perspective Analytical Models (Charts Page)

The Charts Page serves(4.4) as the system's advanced diagnostic engine, offering five distinct perspectives on household consumption:

- **Temporal & Instantaneous Monitoring:** The Energy Meter (speedometer gauge) provides a real-time readout of demand, while the Radial Graph maps consumption over a 360-degree scale to identify cyclical usage patterns.
- **Economic Impact:** The Cost Chart performs a comparative analysis of daily expenditures, featuring a "Raise" indicator that calculates the percentage increase or decrease relative to previous periods.

- **Spatial Energy Attribution:** The system bridges the gap between data and physical space via a Heatmap Matrix, which displays hourly room-by-room consumption. This is complemented by an Architectural View—a 2D floor plan heatmap that uses color gradients to pinpoint high-intensity demand areas (e.g., Kitchen vs. Bedroom) in real-time.

Administrative and Behavioral Feedback

The Members module provides a robust administrative interface where users can add, edit, or delete profiles. Each member is linked to a unique Smart Switch ID, ensuring accurate data attribution. Behavioral feedback is reinforced on the Home page through the Price Predictor, which calculates costs based on real-time tariffs, and the Streak of Your Consumption calendar, which tracks longitudinal adherence to energy-saving goals. Finally, the Leaderboard and Device Usage Timeline provide a social and chronological narrative of household activity, encouraging a collective shift toward sustainable energy habits.

These findings established clear prioritization for prototyping: financial immediacy first, invisibility second, family coordination third. Universal themes across cultures confirmed approach validity while Indian-Austrian insights provided deployment preview.

4.6. System Overview

The final dashboard embodies a user-centered design philosophy grounded in established human-computer interaction principles while addressing the unique challenges of family energy monitoring. Every interface decision emerged from systematic user research and iterative refinement guided by both classical HCI theory and empirical testing with diverse family members.

User control and freedom (Norman's principle [57]) manifests throughout the system. Users determine what information they view, when they view it, and how deeply they engage. The dashboard never forces actions, prescribes behaviors, or restricts access to information. Parents can configure privacy settings according to their family's unique norms rather than accepting imposed restrictions. All family members can customize their experience choosing notification preferences, interface themes, and default views ensuring the system adapts to users rather than demanding users adapt to it. Critically, users maintain the freedom to disengage: closing the dashboard requires no complex exit procedures, and temporarily ignoring the system carries no penalty. This respect for user autonomy proved essential during field deployment, where some family members engaged intensively while others checked sporadically, yet both patterns were equally valid and supported.

Recognition over recall (Nielsen's heuristic [55]) reduces cognitive burden by making information visible rather than requiring memorization. Device names match physical appliances "Living Room TV" not "Shelly_Device_01" eliminating the need to remember abstract identifiers. Color coding remains consistent across all views: green always indicates low consumption, red signals high usage. Users need not remember yesterday's consumption to assess whether today is normal; comparison statistics appear automatically alongside current values. Navigation labels combine icons with text, ensuring users recognize destinations rather than relying on icon interpretation. This principle particularly benefits intermittent users who might check the dashboard weekly rather than daily; they encounter a familiar interface requiring no re-learning even after extended absence.

Consistency across all views creates predictable interaction patterns that reduce learning curves and prevent errors. The color-coded gauge appears identically formatted on the homepage, device pages, and historical views, building recognition through repetition. Navigation elements occupy the same screen positions throughout the application, enabling muscle memory development. Interactive elements behave identically hover states, click actions, and transitions function uniformly regardless of context. This consistency extends to language: the system never calls energy consumption "usage" on one screen and "draw" on another, maintaining terminological uniformity that prevents confusion.

Progressive disclosure of complexity serves users across the technical literacy spectrum by revealing information gradually rather than overwhelming novices with comprehensive data displays. The homepage presents essential information current status, today's total, top consumers in simplified formats accessible to children and casual users. Users seeking additional detail can drill down: clicking devices reveals individual histories, selecting time periods exposes granular hourly data, and accessing settings unveils advanced customization. This layered architecture means an eight-year-old checking if their gaming is "good or bad" sees immediate green/yellow/red indication, while a parent investigating monthly patterns can access sophisticated analytical views. Complexity exists but hides behind optional interactions, ensuring it enriches rather than burdens the experience.

Accessibility to ages 6-65+ required deliberate accommodation of cognitive, visual, and motor differences across lifespan development. Visual design employs redundant encoding color plus text labels, icons plus words ensuring color-blind users lose no information. Text sizing follows WCAG standards. Language simplifies technical concepts: "electricity used" replaces "energy consumption," "currently using" supplants "instantaneous power draw." Cognitive load management limits simultaneous choices to three-to-five options, preventing decision paralysis particularly important for elderly users and children.

Designed for quick checks rather than prolonged analysis, the system respects that energy monitoring is peripheral to daily life, not a primary activity demanding sustained attention. Core information "Are we doing well today?" becomes answerable within three seconds of opening the dashboard through the prominent color-coded gauge and comparative statistics. Most common tasks checking daily total, viewing top consumers, confirming devices are off require zero to two clicks and complete within one minute. This efficiency emerged directly from field deployment observations revealing that family members rarely engaged for more than 2-3 minutes per session. The interface optimizes for these quick check-ins rather than assuming users want comprehensive analytical sessions, acknowledging that effective energy awareness requires regular brief engagement more than occasional deep analysis.

Real-time energy tracking

The real-time view provides instantaneous visibility into current household consumption. A large circular gauge displays total power draw in Watts with color-coded zones indicating consumption levels relative to household norms. This design choice aligns with evidence that immediate feedback increases awareness and encourages behavioral reflection [20]. Below the gauge, individual device cards show each monitored appliance's current state (on/off) and power consumption. Devices currently on appear highlighted with active animations (subtle pulsing) drawing attention to consumption sources. The display updates every 30 seconds, balancing responsiveness with system load.

Implementation employs React state management to poll the Home Assistant API at regular intervals, updating component state which triggers re-renders with new values. Animated transitions between values (rather than instant jumps) help users notice changes without jarring disruption. The gauge visualization uses D3.js for smooth SVG rendering capable of scaling to different screen sizes.

Historical data visualization

Historical analysis enables pattern recognition over hours, days, and weeks through multiple coordinated views. The daily view presents hourly consumption as a bar chart for the selected day, with tooltips revealing precise values and device breakdowns for each hour. A date picker enables comparison across different days. The weekly view aggregates days into a seven-bar chart showing total consumption by day of week, revealing whether weekends differ from weekdays. The monthly view shows daily totals across the calendar month, enabling identification of unusually high or low consumption days.

All historical views share consistent visual styling and interaction patterns clicking any bar drills down to finer granularity (monthly $\longrightarrow$ daily $\longrightarrow$ hourly), right-clicking returns to higher level, and color scales consistently represent consumption intensity. Historical data visualization enables pattern recognition across time periods, supporting comparative evaluation strategies shown to influence energy-saving behavior [54]. Implementation queries Home Assistant's history API with appropriate start/end timestamps, aggregates results client-side using JavaScript reduce operations, and renders using Recharts library chosen for its React integration and responsive design.

A unique device comparison view displays stacked area charts showing each device's contribution to total consumption over time, revealing not just totals but composition for instance, showing that while total consumption dropped, the proportion from entertainment devices actually increased. This visualization required custom development as standard chart libraries don't easily support the precise stacking and labeling requirements.

User-friendly interface elements

Beyond visualizations, numerous interface elements enhance usability for diverse family members. Large touch targets (minimum 44x44 pixels) accommodate both children's less precise interactions and mobile touch input. Clear visual feedback for all interactions buttons change color on hover, selections highlight, actions trigger confirmation messages ensures users understand system responses.

Help text appears contextually throughout the interface small question mark icons beside complex features reveal explanatory tooltips on hover, first-time user tutorials guide initial navigation, and an FAQ section addresses common questions. This layered help system provides assistance without cluttering the interface for experienced users who don't need it.

Accessibility features ensure usability for family members with visual impairments or other disabilities. Color is never the sole information carrier consumption levels use both color and numerical indicators; device states show both color and text ("ON"/"OFF"). Sufficient color contrast ratios follow WCAG AA standards. Keyboard navigation enables complete dashboard control without mouse/touch, critical for motor impairment accommodation.

Multi-user considerations

Supporting simultaneous family usage required careful feature design balancing individual and collective perspectives. Each family member receives a personal login enabling customized views and privacy controls. The member dashboard shows that individual's associated devices prominently while displaying family totals contextually. Parents can designate certain devices as shared (appearing in everyone's view) or private (visible only to specific members).

The family overview aggregates everyone's consumption into comparative displays—a pie chart showing each member's contribution percentage, and a leaderboard-style ranking (optionally hidden if parents prefer avoiding competition). Importantly, this view emphasizes collective achievement rather than individual blame *Our family saved 15% this week* rather than *Dad used 40% more than everyone else.*

Implementation stores user profiles and device associations in a separate configuration file read by the dashboard application. React context provides current user identity throughout the component tree, enabling conditional rendering based on permissions. The backend API filters queries to return only devices the requesting user has permission to view.

Mailing Pipeline

Technical implementation uses Home Assistant's automation system to monitor for trigger conditions template sensors detecting anomalies, time-based triggers for summaries which call webhooks in the dashboard application. Email delivery employs SMTP protocol to send formatted HTML emails containing consumption highlights and links back to detailed dashboard views.

Developed an automated email system using the SMTP protocol to deliver daily consumption reports. Each report is generated as a PDF containing granular data for specific users and switches, including timestamps, energy usage in kWh, and total costs, complemented by a visual consumption graph.

4.7. Refinement and Deployment

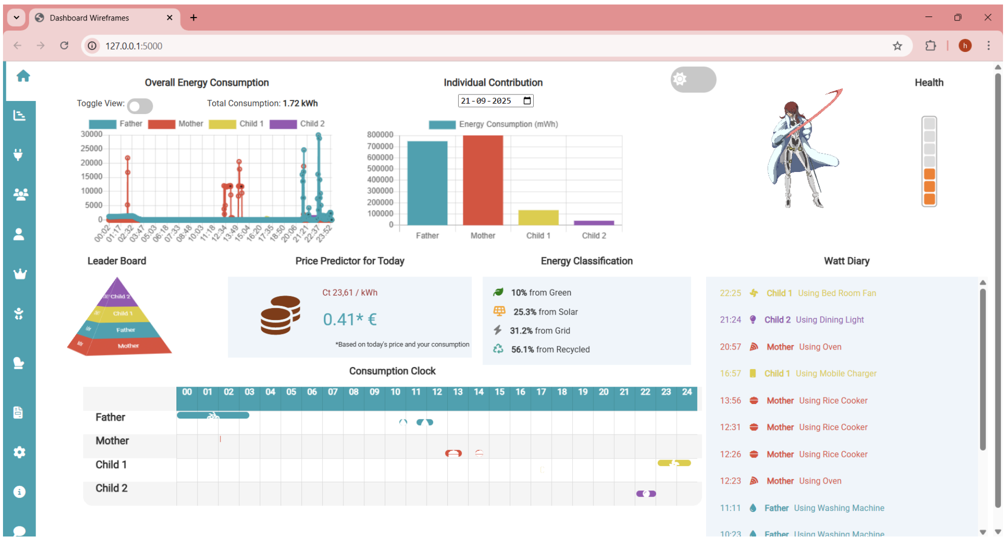

Figure 4.5.: final developed model of the dashboard

The final developed model of the WattExplorer dashboard, as observed in Figure 4.5 successfully translates the qualitative findings from the Braun and Clarke thematic analysis into an interface that users found "pleasing to the eyes" and "easy to interact" with. The design effectively bridges the "awareness gap" identified in Theme 1 (Invisibility) by utilizing real-time Overall Energy Consumption graphs and a detailed Watt Diary, which provide the sensory feedback and device attribution previously missing for users. Centering the Price Predictor widget satisfies Theme 2 (Economic), ensuring that financial savings—the primary user motivator—remain the focal point through prominent Euro-based metrics.

To address Theme 3 (Phantom), the Energy Classification section provides actionable insights into standby and "vampire" power, facilitating the behavioral control users desire. The tension between household unity and individual accountability (Theme 4: Coordination) is resolved through the Leader Board and Individual Contribution charts, which promote "friendly rivalry" while maintaining collective family goals.

Furthermore, Theme 5 (Privacy) is managed through granular Toggle View switches, allowing users to define boundaries and mitigate surveillance concerns. Finally, Theme 6 (Usability & Complexity) is addressed through the Consumption Clock and the implementation of Dark Mode with a button.

Users found the Dark Mode which can be enabled from a switchable button as seen in Figure 4.6 particularly informative for pre-sleep checks, and the dark mode version can be observed in 4.7, allowing them to review their personal contributions and set specific energy goals for the following day in a low-fatigue environment. By grounding these features in empirical themes, the dashboard transforms abstract data into a tool for

Figure 4.6.: Slider button for enabling/disabling the darkmode

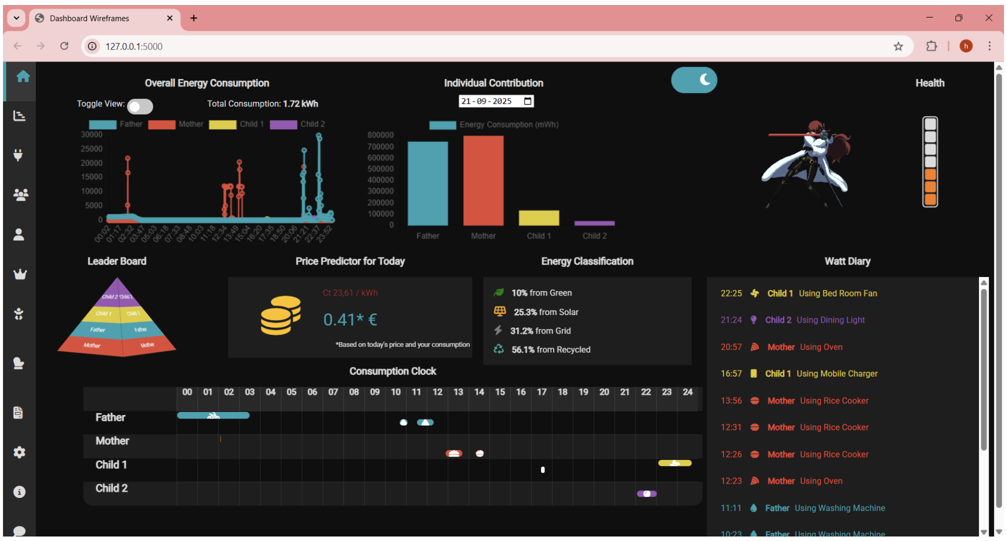

Figure 4.7.: View of dashboard in darkmode

sustained behavioral change.

4.7.1. Breakdown of every visualization model

Navigational Architecture and System Observation

The sidebar menu serves as the primary navigation hub(Figure 4.8), allowing users to switch between different lenses of energy observation. This structure operationalizes the study's findings by categorizing complex data into digestible, task-oriented views:

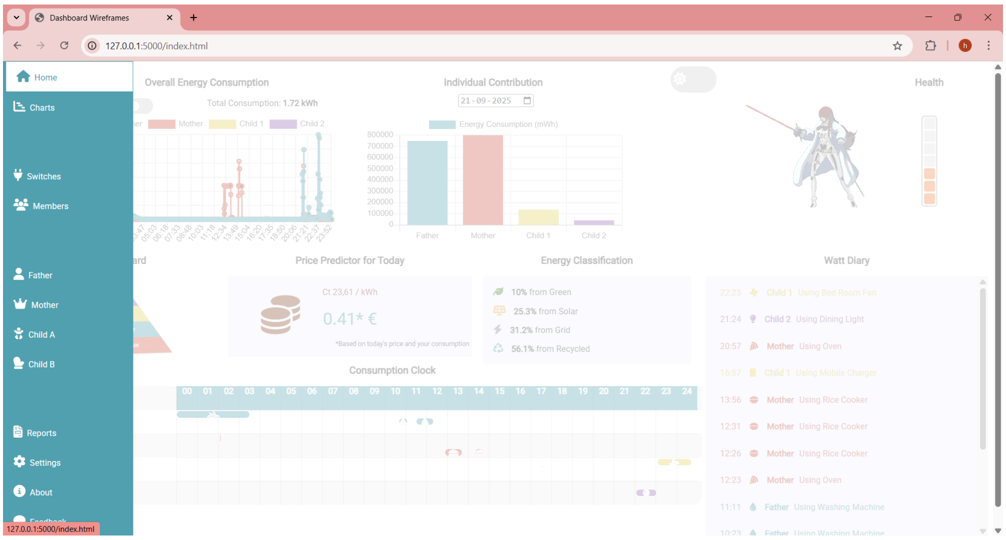

Figure 4.8.: Hamburger menu showcasing the primary system navigation

Primary System Navigation:

- **Home:** Provides a high-level overview of real-time consumption and financial impact for immediate awareness.
- **Charts & Reports:** Offers deep-dive analytical views for historical trend analysis, addressing the need for contextualizing consumption data.
- **Switches:** Centralizes control for smart device management, directly supporting behavioral change mechanisms.
- **Individualized Member Views:** The menu includes dedicated profiles for each household member (Father, Mother, Child A, Child B), enabling the individual accountability and "friendly rivalry" identified as a key motivator in the thematic analysis.
- **Settings & About:** Includes granular privacy controls to mitigate surveillance concerns while ensuring the platform remains WCAG-compliant and accessible to all ages.

Home Page

Timeline of Overall consumption

This timeline(Figure 4.15) follows the HCI principle of visibility by providing live energy feedback. It lowers cognitive load by mapping household activities to energy spikes on a familiar 24-hour clock. This allows users to learn their habits through simple observation.

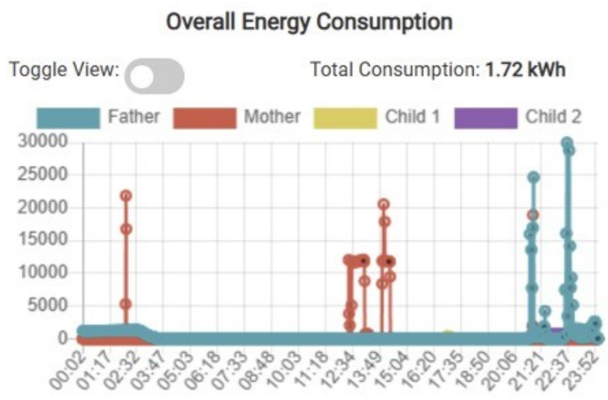

Figure 4.9.: Overall Energy Consumption Timeline Toggle Chart

The Overall Energy Consumption module operationalizes Theme 1 (Invisibility) by visualizing family usage on a 24-hour timeline. The interface features a "Toggle View" switch for transitioning between line and bar charts, facilitating varied analytical perspectives. By integrating a color-coded legend for individual members and a prominent total consumption metric (1.72 kWh), the dashboard renders abstract data into a functional interactive experience. This design effectively transforms electrical consumption into a tangible, data-driven tool for domestic energy management.

Individual Usage Breakdown

This clear mapping of data to specific users(Figure 4.10), leverages recognition over recall, making it easy to identify high consumers. By providing immediate feedback on personal behavior, the system reduces the gulf of evaluation, empowering individuals to adjust their actions to meet shared family goals.

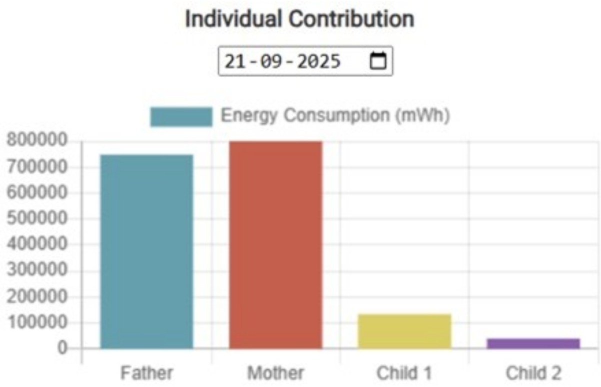

Figure 4.10.: Block chart of family members contributions

The Individual Contribution chart applies HCI principles of social proof and accountability by visualizing personal energy use compared to the household.

Avatar Character

The animated avatar serves(Figure 4.11) as a visual metaphor for the family's total energy health. Linked to the Overall Energy Consumption, a threshold-based health bar decreases block by block as usage rises.

Figure 4.11.: WattExplorer Avatar

Using the HCI principle of feedback, the avatar's movement speed reflects these levels slowing down at low points and moving fast at full health. This gamified approach translates complex consumption data into an intuitive signal for the entire household.

Leader Board

The Leader Board(Figure 4.12) employs a pyramid visualization to represent energy conservation rankings, where the member at the apex has achieved the highest savings.

From an HCI perspective, this utilizes social competition and gamification to encourage sustainable habits.

Figure 4.12.: Leaderboard showing who leads the day w.r.t consumption

The clear hierarchical structure provides immediate social feedback, transforming abstract data into a "friendly rivalry" that drives engagement. By making individual performance visible within the group, it strengthens accountability and collective motivation.

Price Predictor

The Price Predictor(Figure 4.13) widget transforms abstract energy metrics into a concrete financial value. By applying the provider's standard rate per kWh, it provides a real-time cost estimate. This direct mapping to currency simplifies decision-making, satisfying the user's primary economic motivation.

Figure 4.13.: Price Predictor based on the current consumption

Energy Classification

The Energy Classification widget as shown in Figure 4.14 provides essential context by visualizing the primary sources of the household's electricity, with data derived from the E-Control website regarding their specific provider. From an HCI perspective, this feature addresses Theme 2 (Environment as Secondary) by making the environmental impact of consumption visible and easy to interpret.

Figure 4.14.: Energy Classification classifying from where the energy comes

By breaking down usage into categories such as Solar (25.3%), Grid (31.2%), and Recycled (56.1%), the system offers high transparency, allowing users to understand how their energy is generated. This clear information design helps users bridge the gap between abstract utility bills and the real-world environmental consequences of their daily habits.

Consumption Clock

The Consumption Clock visualizes energy use on a 24-hour timeline as the following Figure 4.15, mapping specific device logos to individual family members to show exactly when and for how long appliances were used. From an HCI perspective, this supports recognition over recall through iconic representation, while hover interactions provide detailed feedback without increasing visual clutter.

Figure 4.15.: Consumption Timeline dragging the information on what and who is used w.r.t to the time

By making hidden habits visible, the system lowers cognitive load and helps users relate personal activities directly to their energy impact.

WattDiary

The Watt Diary (Figure 4.16) provides a chronological log of personal energy events, detailing which household member used a specific device at a precise time. From an HCI perspective, this supports Theme 5 (Individual Accountability) by eliminating ambiguity around energy consumption through granular activity tracking.

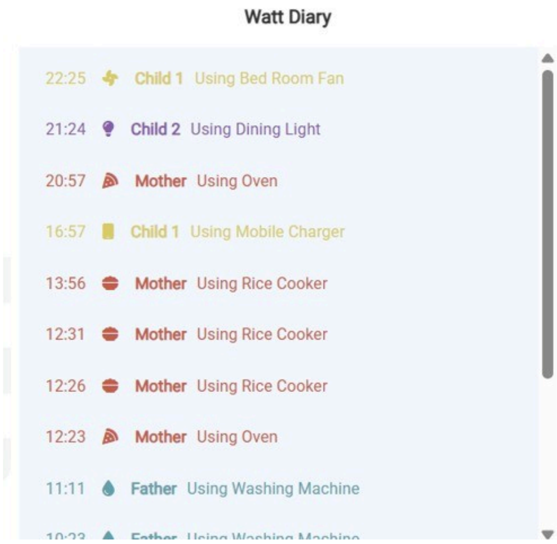

Figure 4.16.: Watt Diary detailing who uses what and when

By presenting data in a scannable list format, the system leverages recognition over recall, allowing users to easily identify usage patterns such as the Mother using the oven or a child using a mobile charger without having to remember past actions. This high-resolution feedback bridges the "awareness gap" by making previously invisible habits directly observable and attributable.

Member selection and Highlighting

Adult member highlighting

The dashboard uses synchronized highlighting to manage the relationship between household and individual data. When a user is selected, their data is highlighted across all graphs while other information is , the difference when member Mother is selected is observed in Figure 4.17.

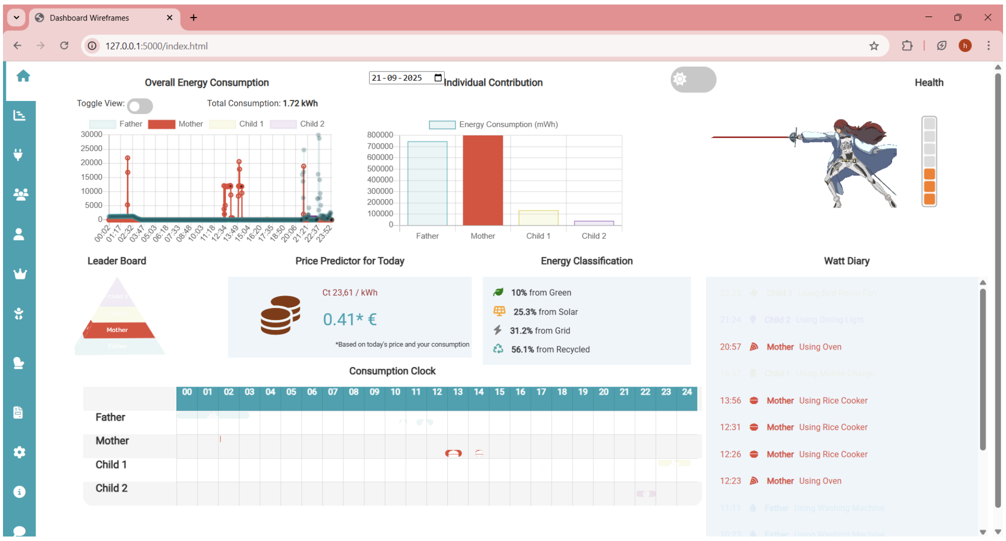

Figure 4.17.: Member Highlighting (Mother)

From an HCI perspective, this approach provides several benefits:

- **Individual Accountability:** It makes a person's specific contribution to the total energy use immediately visible, supporting the need for individual identity within the family unit.
- **Reduced Cognitive Load:** Highlighting allows users to focus on one person's impact without losing the overall context of the household.
- **User Control:** Centralizing these selections in the home menu makes the system flexible and easy to navigate based on what the user wants to see.

Child member highlighting

The dashboard features customizable themes for children when highlighted (Figure 4.18), allowing them to select fun background patterns and characters during the member creation process. This idea originated from pre-development interviews with children to ensure the interface was engaging for younger users

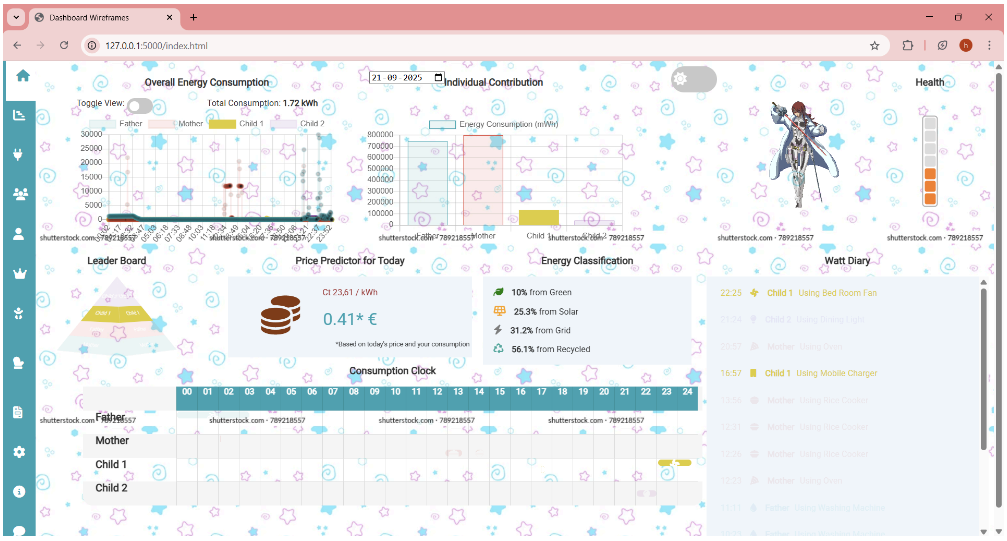

Figure 4.18.: Memberhighlighting (Child with a theme choice)

From an HCI perspective, this feature uses personalization to increase emotional investment and long-term engagement. It follows age-appropriate design principles by creating a playful, less intimidating environment for energy monitoring. By tailoring the visual experience, the system makes complex data accessible and fun for children, supporting the research theme of usability and engagement.

Device Specific Data

The Charts Page serves as an analytical deep-dive into device-specific performance by selecting them by a drop down menu(Figure 4.19), allowing users to isolate consumption patterns regardless of individual attribution. From an HCI perspective, this page fulfills the need for system transparency and historical context, helping users identify "energy-hungry" appliances over time(Figure 4.22).

Interactive Functionality

The interface allows users to change different devices from a dropdown menu to observe their usage and it also allows to change the date to observe device usage over different days finally there is an option to toggle between Total Daily, Last Hour, and Last 15 Minutes views, supporting both long-term planning and immediate behavioral adjustments. By selecting specific devices from a dropdown menu (e.g., Oven), users can filter out the "noise" of general household usage to focus on specific high-impact areas. This targeted feedback addresses Theme 3 (Behavioral Attribution and Control) by giving users the exact information needed to manage household power effectively.

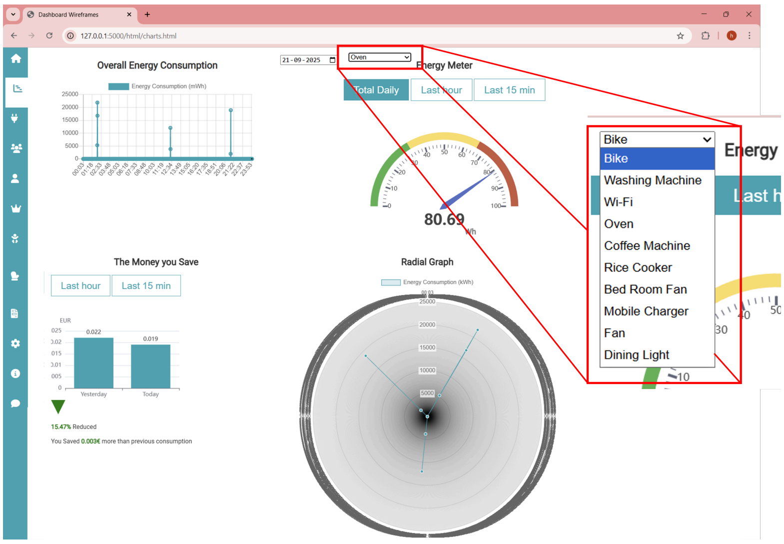

Figure 4.19.: Interactive functionality for selecting different switches data

Device-Specific Analytical Components

- **Overall Device Consumption(Figure 4.20):** A line graph tracking a specific device's usage throughout a selected date, allowing for precise trend identification.
- **Energy Meter(Figure 4.20):** A high-visibility radial gauge providing instantaneous feedback on a device's current draw (e.g., 80.69 Wh for an oven), color-coded to indicate usage intensity.

Figure 4.20.: Timeline and Electrometer in Charts Page

- **"The Money You Save"(Figure 4.21):** A comparative bar chart that maps consumption reduction directly to financial savings in Euros, reinforcing the primary economic motivator found in Theme 2.
- **Radial Data Visualization(Figure 4.21):** A specialized polar chart representing energy consumption (kWh) over time, offering a unique spatial perspective on usage peaks.

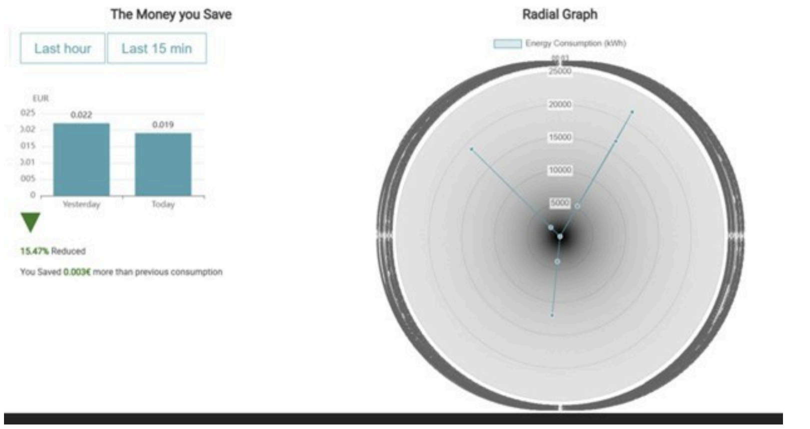

Figure 4.21.: Economic Point of View and Radial Chart of Usage

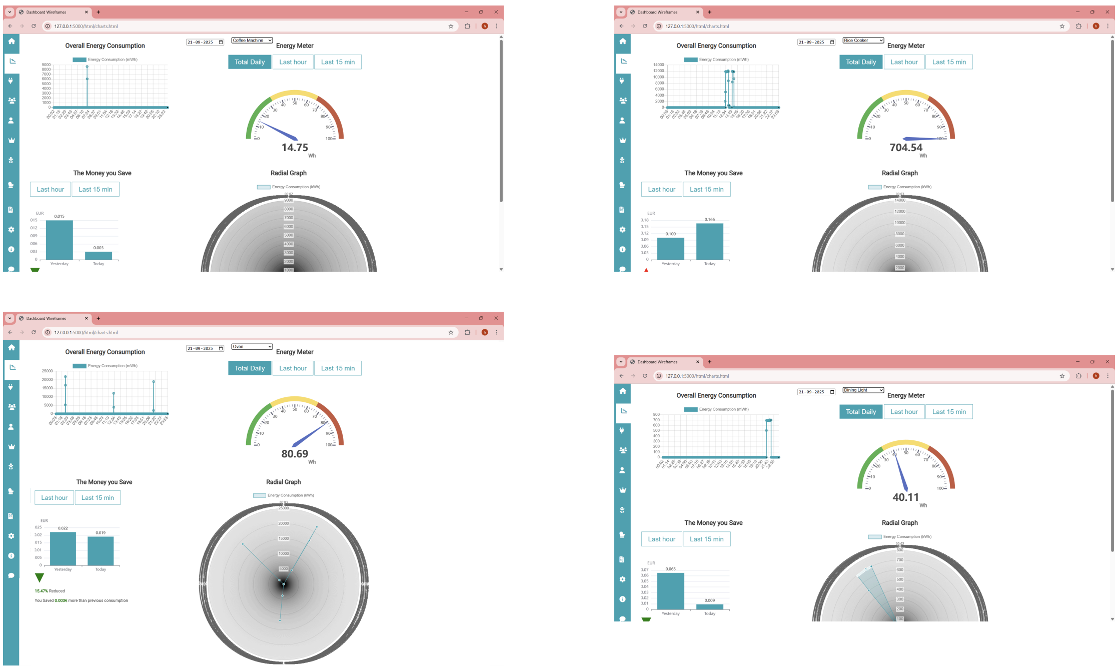

Figure 4.22.: Overview of the different switches and their consumption (for comparision); Device information- Coffee Machine (top-left), Rice Cooker (top-right), Oven (bottom-left), Dining Light(bottom-right)

Switches Information

The Switches Page centralizes control and monitoring of household smart devices(Figure 4.23), mapping individual responsibility to physical hardware. From an HCI perspective, this page facilitates direct action and provides high system visibility, addressing the gap between energy awareness and behavioral control. Device Control and Ownership Management

- **Personal Allocation:** The interface clearly lists which devices (e.g., Washing Machine, Rice Cooker, Mobile Charger) are allocated to specific family members, reinforcing the individual accountability identified in the research themes.
- **Real-Time Status Monitoring:** High-contrast toggle switches provide immediate feedback on the current "Switch Status" (On/Off), allowing users to quickly identify and manage active energy loads.
- **Technical Transparency:** The inclusion of "Switch IP" addresses provides technical clarity for household device management, ensuring users have a precise digital map of their smart home network.

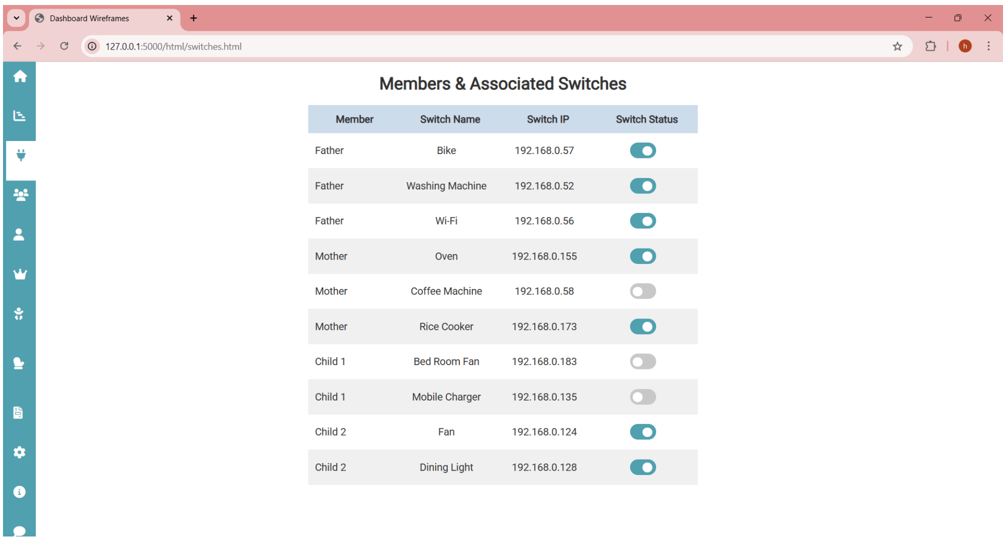

Figure 4.23.: Switch specific information page

This centralized view empowers users to act on the insights gained from the Charts Page. By seeing their personal list of assigned devices, members can take ownership of their specific "phantom loads" or high-consumption appliances, directly supporting Theme 3 (Behavioral Attribution and Control).

Members Directory The Members Page acts as the administrative center for household energy management, providing a transparent map of device ownership and user identity(Figure 4.24). Administrative Functionality and Personalization

- **Device Allocation and Network Mapping:** The page explicitly links specific smart switches (e.g., Bike, Washing Machine, Rice Cooker) to individual members, displaying both the device name and its unique IP address for technical clarity.
- **Visual Identity Management:** Users can define their "Preferred Color," which serves as the primary visual identifier for their data across all dashboard graphs, supporting the HCI principle of consistent mapping.
- **Child-Centric Personalization:** A specific "Child Profile" toggle enables a "Theme" selection feature, allowing younger users to choose playful background aesthetics (e.g., "Tom & Jerry") that increase emotional engagement.
- **Profile Management:** Dedicated editing icons allow for the modification of existing member details, while the layout facilitates the seamless addition of new household members to the system.

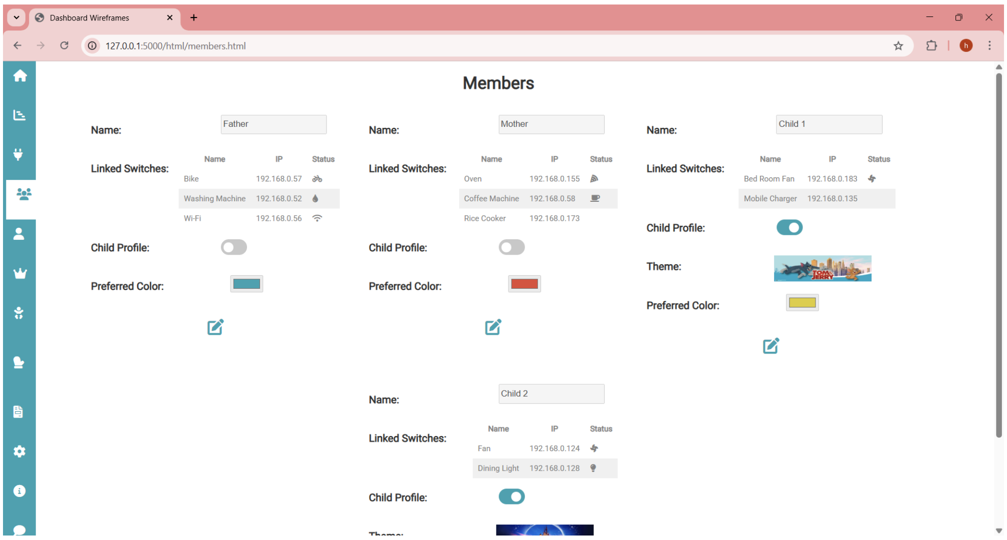

Figure 4.24.: Collective Members Data

From an HCI perspective, this page reduces the gulf of execution by providing a central location for managing the system's social and technical structure. By clearly defining who is responsible for which device, the interface transforms abstract household energy use into a manageable social contract, directly fulfilling Theme 5 (Family as Collective but Individualized Unit).

Report generation

The Reports Page(Figure 4.25) functions as the primary archival and communication hub of the system, providing a high-level summary of daily consumption and costs. It consolidates family data into a formal document that can be customized by date. Data Aggregation and Dissemination

- **Total Daily Metrics:** The page prominently displays the "Total Consumption" (e.g., 1.72 kWh) and "Total Cost" (e.g., 0.41 EUR) for a selected date, simplifying the family's overall financial impact.
- **Granular Member Breakdown:** It provides a specific breakdown for each member (e.g., Mother, Father, Children), showing their individual kWh contribution and the corresponding monetary cost.
- **Device-Level Specifics:** Under each member, the report lists precise consumption for their allocated devices, such as a Rice Cooker (704.54 Wh) or a Washing Machine (523.77 Wh).
- **Automated and Manual Exporting:** The system is designed for high accessibility; it automatically emails a previous day's report to a predefined address at 12:00 AM. Additionally, users can manually enter an email address to "Generate and Email Report" on demand.

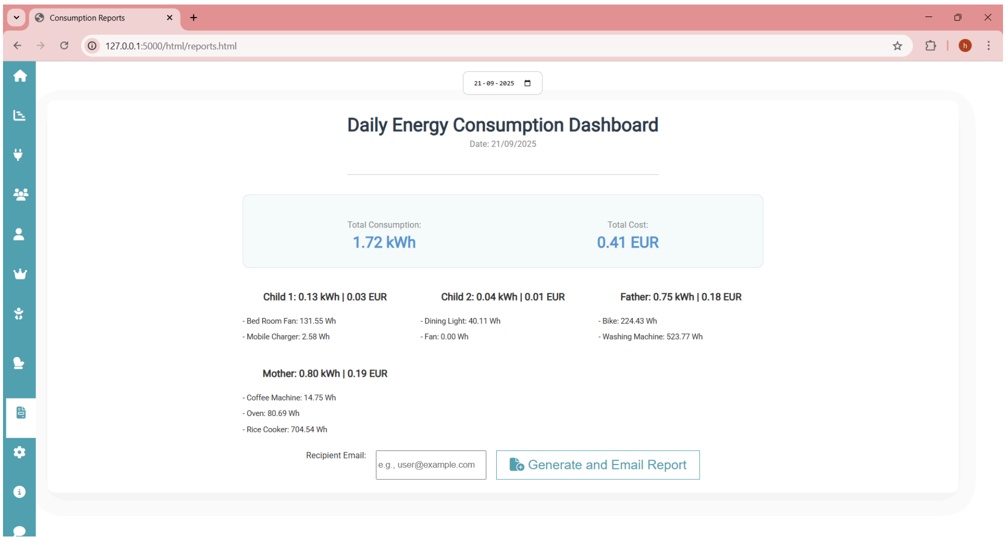

Figure 4.25.: Export report page giving the detailed information for a documentation work

From an HCI perspective, this page directly satisfies Theme 1 (Invisibility) and Theme 2 (Economic Motivations) by transforming ephemeral usage into a permanent, shareable record. By delivering this data directly to a user's inbox, the system reduces the gulf of evaluation, ensuring that members stay informed about their financial and environmental footprint without needing to actively check the dashboard.

Feedback section

The Feedback Page(Figure 4.26) allows users to quickly share their feelings about the dashboard using simple icons for "Unhappy," "Neutral," or "Satisfied". From an HCI perspective, this provides a direct channel for qualitative feedback, helping researchers understand the user's emotional experience. By recording these responses, the system supports iterative design, ensuring future improvements are based on real user satisfaction and needs.

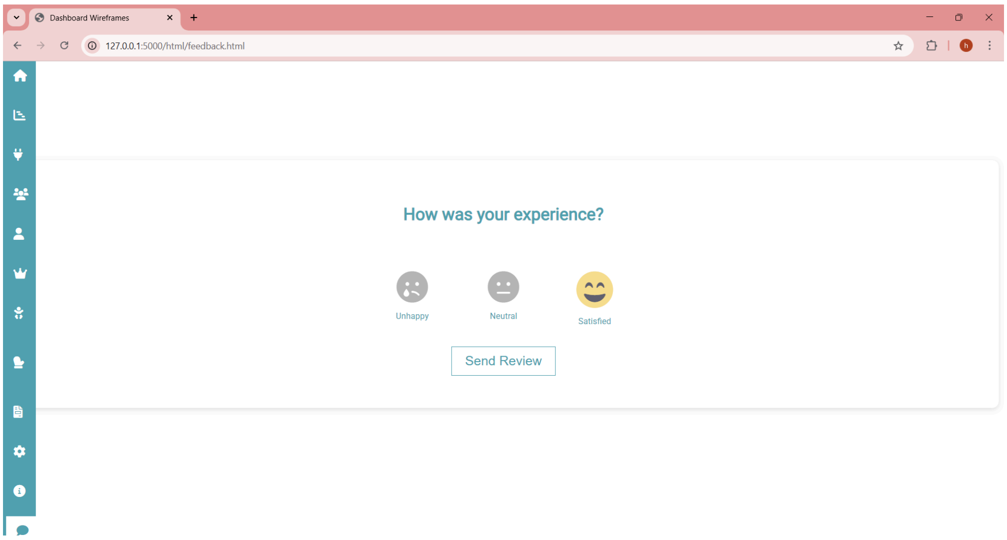

Figure 4.26.: Feedback section for continuous development

About Section

The About Page(Figure 4.27) serves as an onboarding tool that helps new or non-users quickly understand the dashboard's purpose and goals. By explaining metrics like Carbon Emissions and Cost Analysis, it builds a clear mental model of how the system tracks energy. From an HCI perspective, this simple one-shot explanation improves transparency and makes the system's objectives easy to see, helping users feel confident as they begin exploring their data.

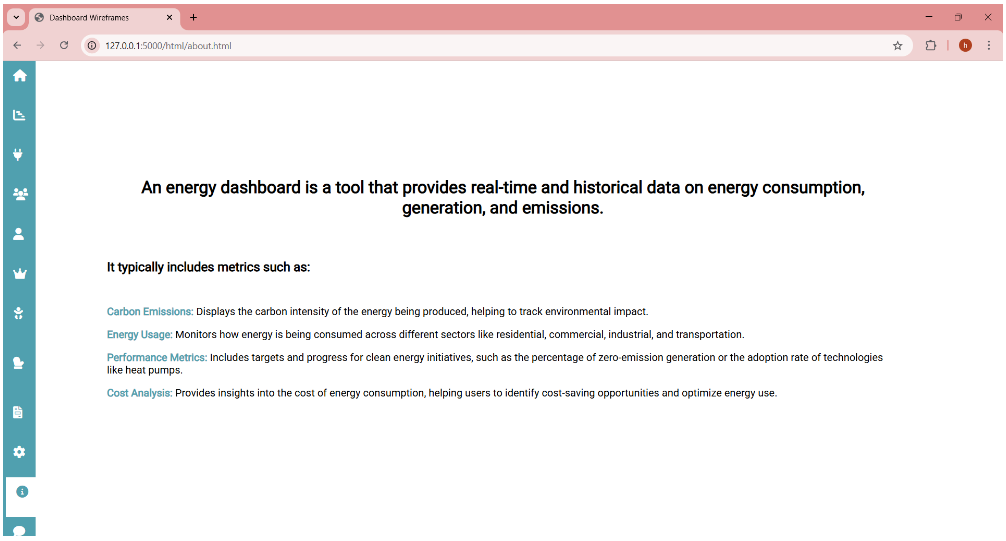

Figure 4.27.: About page explaining what the dashboard gives us (for non users)

4.8. System Architecture and Technical Implementation

The technical architecture integrates commercial smart home hardware with open-source software platforms and custom dashboard development to create a complete energy monitoring ecosystem. The design prioritizes reliability, data accuracy, local processing for privacy, and extensibility to accommodate future enhancements. This section details the hardware components, software infrastructure, and data flow that enable real-time device-level energy monitoring accessible through an intuitive web interface.

4.8.1. Smart switch integration (Shelly outlets + Raspberry Pi)

The foundation of energy monitoring relies on Shelly Plug S smart outlets, compact Wi-Fi-enabled devices that measure power consumption while providing remote control capabilities [8]. Each Shelly plug monitors voltage, current, instantaneous power (Watts), and cumulative energy consumption (kWh) with reported accuracy of $\pm 1\%$ for energy measurement. The devices update consumption data every 1-2 seconds, providing near real-time feedback suitable for observing immediate effects of device state changes. Shelly plugs were selected over alternatives due to their local API access (not requiring cloud connectivity), open integration possibilities, competitive pricing ($\sim$ 20 euros per unit), and compact form factor that minimizes outlet blockage.

Strategic deployment of Shelly plugs focused on major household energy consumers and devices with variable usage patterns. High-priority monitoring targets included entertainment systems (television, game consoles), computing devices (desktop computers, monitors), kitchen appliances (microwave, coffee maker), and always-on devices (Wi-Fi router, cable modem). While comprehensive whole-home coverage would require 20-

30 plugs exceeding budget constraints, monitoring 8-12 key devices captures 60-70% of controllable household consumption, sufficient for meaningful insights and behavior change potential.

The Raspberry Pi 5 [61] serves as the central processing hub, running continuously to collect data from Shelly devices, execute the Home Assistant platform, host the database, and serve the dashboard web application. The Pi's quad-core processor and 4GB RAM provide adequate performance for these tasks while maintaining low power consumption ($\sim 5W$) and silent operation suitable for permanent household deployment. A 64GB microSD card provides storage for the operating system, Home Assistant installation, and local database. The Pi connects to the home network via Ethernet, ensuring stable connectivity more reliable than Wi-Fi for a critical infrastructure component.

4.8.2. Home Assistant setup

Home Assistant, an open-source home automation platform, provides the middleware layer between Shelly devices and the custom dashboard. Rather than implementing direct communication protocols with each smart device, Home Assistant offers pre-built integrations supporting thousands of devices, unified APIs for accessing their data, and automation capabilities enabling intelligent system behaviors.

The Shelly integration in Home Assistant automatically discovers devices on the local network, establishes communication via their HTTP APIs, and polls for updated consumption data at configurable intervals (set to 10 seconds for this deployment, balancing responsiveness with network load). Home Assistant normalizes the varying data formats from different Shelly models into consistent entity representations, each exposing current power, cumulative energy, and device state (on/off) as readable attributes.

Home Assistant's recorder component logs all entity state changes to a SQLite database, creating the historical record necessary for trend analysis and behavior pattern identification. Retention policies preserve detailed data for 30 days with aggregated hourly summaries retained indefinitely, balancing granular recent history with long-term trend visibility while managing storage constraints.

The Home Assistant web interface provides administrative access for system configuration but is not the primary user-facing dashboard. Its technical presentation targets system administrators rather than general family users, motivating development of the separate custom dashboard with family-appropriate design.

4.8.3. Data flow and storage

Data flows through multiple stages from physical measurement to user-visible visualization. At the measurement layer, Shelly plugs sample electrical parameters hundreds of times per second internally, aggregating these into reported values updated 1-2 times per second. Home Assistant polls each Shelly device every 10 seconds via HTTP requests to their local IP addresses, retrieving current readings. Upon receiving updates, Home Assistant compares new values against previous states if power consumption changed by more than

5% or device state toggled, the change is logged to the SQLite database with precise timestamps.

The database schema centers on a states table recording every entity state change:*entity_id* (which device), *state* (current value), attributes (JSON containing all measurement details), and *last_updated* (timestamp). This event-sourced design preserves complete history rather than just current values, enabling reconstruction of consumption patterns at any granularity. Additional tables store entity metadata, statistical summaries, and automation execution logs.

The custom dashboard application, built with React and TypeScript, runs as a separate web server on the Raspberry Pi (port 3000), distinct from Home Assistant's interface (port 8123). The dashboard queries Home Assistant's REST API to retrieve both real-time current states and historical data from the database. API endpoints provide current entity states ($/api/states/ < entity\_id >$), historical state changes within time ranges ($/api/history/period/ < start\_time >$), and statistical aggregations. The dashboard caches frequently accessed data client-side to minimize API load and improve responsiveness, refreshing every 30 seconds for real-time views.

Data storage employs a hybrid approach balancing privacy and accessibility. All consumption data resides locally on the Raspberry Pi's storage no external cloud services receive household usage information, addressing privacy concerns about third-party data access. However, the dashboard itself is accessible from any device on the home network, enabling family members to check consumption from smartphones, tablets, or computers. A reverse proxy with authentication could enable remote access from outside the home network if desired, though this introduces security considerations requiring careful implementation.

4.9. Technical Challenges and Solutions

Despite careful planning, deployment encountered several technical challenges requiring problem-solving and design adjustments.

4.9.1. Data accuracy issues

Initial testing revealed potential discrepancies between smart plug measurements and utility meter readings, a concern raised by one pre-deployment interview participant with prior smart switch experience. Limited validation comparing dashboard-reported consumption against utility bills suggested minor variances, though insufficient testing prevents definitive accuracy claims.

Smart plugs like Shelly devices measure apparent power (Volt-Amperes) while utilities bill for real power (Watts). For devices with reactive loads such as motors and transformers, this measurement difference can cause discrepancies. Additionally, polling intervals may miss brief high-power events like microwave heating cycles.

For the field deployment, periodic spot-checks comparing dashboard totals against utility bills showed general alignment sufficient for the system's purpose of revealing consumption patterns and supporting behavior change. The emphasis throughout deployment was on relative comparisons, identifying which devices consume more, whether consumption is increasing or decreasing, rather than absolute precision, which proved adequate for driving conservation awareness and action.

4.9.2. Total consumption monitoring approaches

Shelly plugs monitor only devices they're installed on, missing unmonitored appliances and permanently wired systems like HVAC and lighting. Two approaches addressed whole-home totals. The first involved a clamp-on current sensor (CT sensor) attached to the main electrical panel measuring total household current. This required professional electrician installation for safety and accuracy, adding cost and complexity. The second leveraged the utility smart meter's data, accessible via Home Assistant integration with the utility provider's API.

The smart meter approach ultimately proved superior professionally calibrated, no installation required, complete household coverage. However, it introduced 30-60 minute data lag as meters only report every hour, making real-time feedback impossible. The solution employed a hybrid: smart meter for authoritative daily/weekly totals, Shelly devices for real-time monitoring, and calculated estimates for the unmonitored remainder (smart meter total minus Shelly-monitored devices).

4.9.3. Integration with existing home systems

The household's existing Wi-Fi network struggled under the additional load of 10+ Shelly devices simultaneously reporting data. Network congestion caused intermittent device disconnections and dashboard loading delays. Solutions included dedicating a separate 2.4GHz Wi-Fi network specifically for smart home devices (isolating them from family internet traffic), upgrading to a mesh Wi-Fi system improving coverage and capacity, and implementing Home Assistant's *device_tracker* to detect and alert about disconnected devices enabling rapid troubleshooting.

Database growth posed unexpected challenges the SQLite database recording every state change grew to multiple gigabytes within weeks, degrading query performance. The solution implemented more aggressive data retention policies (7-day detailed history, 90-day hourly aggregates, permanent monthly summaries) and periodic database maintenance routines compacting and optimizing storage. This balanced comprehensive recent history with manageable long-term storage.

5. User Study and Results

5.1. Field Study

5.1.1. Field study setup and participants

The field deployment occurred in a single-family household comprising four members: father (42), mother/researcher (38), older daughter (11), and younger son (8). The household occupies a three-bedroom townhouse with typical appliances and electronics. The deployment ran for six weeks (August 19 - September 28), capturing both normal routines and holiday periods with altered consumption patterns.

Ten Shelly Plug S devices were installed monitoring: living room TV and gaming console, home office desktop computer and monitor, kitchen microwave and coffee maker, two bedroom devices (daughter's computer, son's gaming device), and utility devices (Wi-Fi router, cable modem). Additional monitoring of total household consumption utilized the utility smart meter integration. Installation required approximately three hours, including Shelly configuration, Home Assistant setup, and dashboard deployment on a Raspberry Pi 5.

Autoethnographic Context: The mother's dual role as both researcher and participant creates unique methodological considerations. As researcher, she designed the system, conducted observations, and maintained reflexive research journals. As participant, she and her family used the dashboard in their daily lives, experiencing genuine consumption feedback and the technology's integration into household routines. This insider position enables observations impossible for external researchers—spontaneous family discussions, authentic frustrations with usability issues, the gradual habituation to technology presence—while requiring careful attention to potential bias in interpretation. Reflexive journaling documented researcher assumptions, design decisions influenced by family feedback, and moments when professional and domestic roles conflicted.

5.1.2. Real-world usage patterns

Dashboard Access Frequency by Family Member: System logs recorded 427 total dashboard accesses over the six-week period, with significant variation by family member and over time. The mother checked most frequently (178 accesses, average 3.2/day initially declining to 1.1/day in final weeks), reflecting both researcher monitoring responsibilities and genuine user interest. The father accessed moderately (94 times, 1.7/day initially, 0.6/day finally), typically during morning coffee and evening relaxation. The older daughter showed burst patterns (89 accesses total)—intense interest for 2-3 day periods followed by week-long gaps, often triggered by specific events like receiving notification badges. The younger son accessed least frequently (66 times), almost exclusively when prompted by family members: "Let's check how we're doing today."

Feature Utilization Analysis: The real-time overview received 312 views (73% of sessions), confirming its role as primary entry point. Historical daily charts were viewed 156 times (37%), weekly summaries 89 times (21%), and monthly trends only 34 times (8%), suggesting diminishing interest in longer-term analysis versus immediate feedback. Device comparison features saw moderate use (112 views, 26%), primarily by the mother and father. The achievement/badge system was checked 67 times, almost exclusively by children.

Interestingly, notification emails saw low engagement only 23% were opened, and clicks-through to dashboard occurred in just 8% of delivered notifications. Follow-up interviews revealed family members checked dashboard proactively rather than waiting for notifications, making alerts feel redundant rather than helpful. Temporal Patterns of Engagement: Dashboard checking concentrated in early morning (6-8am, 28% of accesses) and evening (7-10pm, 41% of accesses), with minimal midday use. Weekend checking patterns differed notably—more mid-morning and afternoon accesses, fewer rigid time patterns, often involving multiple family members viewing together. The first two weeks showed highest engagement (averaging 11 checks/day household-wide), declining to 4-5 checks/day in weeks 3-6, and stabilizing at 3 checks/day in final weeks. This pattern reflects typical novelty effect followed by stabilized habitual use.

5.1.3. Energy consumption changes observed

Quantitative Energy Reduction Measurements: Total household electricity consumption decreased 18.3% comparing the final four weeks of deployment (averaging 24.7 kWh/day) against the four-week baseline immediately pre-deployment (30.2 kWh/day). This reduction equated to approximately 153 kWh monthly savings, translating to estimated EUR 9-15 cost reduction at local electricity rates. While limited to a single household, the magnitude aligns with intervention studies reporting 10–20% reductions through real-time feedback systems [20].

Examining individual monitored devices revealed differential behavior change patterns:

- **Entertainment devices (TV, gaming consoles):** Reduced 31% from 4.2 kWh/-day to 2.9 kWh/day, primarily through reduced standby consumption (devices fully powered off rather than left in standby mode)
- **Computing devices (computers, monitors):** Decreased 24% from 3.8 to 2.9 kWh/day through shorter usage sessions and sleep mode activation
- **Kitchen appliances (microwave, coffee maker):** Minimal change (3%), as these devices are used on-demand regardless of monitoring
- **Always-on devices (router, modem)**: No change (0%), as these cannot be turned off without losing internet connectivity

The differential changes suggest monitoring impacts discretionary/controllable devices more than essential/always-on equipment, as expected. Discretionary loads showed strongest response, consistent with feedback literature [33].

Temporal Pattern Shifts: Beyond total consumption, usage timing shifted measurably. High-consumption activities (laundry, dishwasher, electric vehicle charging added during study) moved toward off-peak hours (9pm-6am), reducing costs under the household's time-of-use electricity rate even when total consumption didn't change. Evening peak consumption (6-9pm) decreased 22% while overnight consumption increased 15%, reflecting conscious load-shifting enabled by dashboard visibility into when energy is consumed.

5.1.4. User engagement metrics

Login Frequency and Duration: Average session duration was 3.2 minutes (median 2.1 minutes), indicating brief, focused checking rather than extended exploration. The mother's sessions averaged longer (5.1 minutes) including administrative tasks and data verification, while children's sessions were briefest (1.4 minutes average), consisting of quick glances at member-specific views and badges.

Session frequency declined over time following a logarithmic decay pattern common in technology adoption studies high initial engagement driven by novelty, followed by stabilization at lower levels representing habitual use. By week 8, the family settled into a pattern of approximately one person checking roughly twice per day, sufficient to maintain awareness without obsessive monitoring. Feature Interaction Patterns: Click-stream analysis revealed typical user journeys through the interface. The most common path (41% of sessions) consisted of: Landing on real-time overview → Viewing personal member tab → Checking daily historical chart → Exiting. A secondary pattern (23% of sessions) involved: Overview → Device comparison → Specific device detail page → Exit. Only 12% of sessions involved exploration of weekly or monthly trends, and advanced features like setting custom goals saw minimal use (7% of sessions). These patterns suggest users sought quick answers to specific questions ("What's our current usage?" "How much did my devices use today?") rather than conducting deep analytical exploration. The interface succeeded at enabling rapid information access, though this may also indicate some designed features didn't provide sufficient value to warrant regular use.

Post-deployment interviews revealed families found value in notifications as reminders to check rather than as primary information sources seeing a notification prompted opening the full dashboard rather than relying on notification content alone.

Collaborative vs. Individual Use Patterns: Dashboard usage split roughly 40% collaborative (multiple family members viewing together), 60% individual. Collaborative viewing occurred more on weekends and correlated with higher engagement—sessions where multiple family members participated averaged 6.3 minutes vs. 2.8 minutes for solo viewing, and generated more feature exploration and discussion.

Individual viewing focused on personal consumption tracking checking one's own devices, verifying responsible behavior, or investigating specific questions. The member-specific features successfully enabled this individual accountability without requiring family consensus for every check.

Age-Specific Engagement Patterns: Clear patterns emerged by family member age and role:

Parents used the dashboard primarily for monitoring and management, checking consumption levels, investigating anomalies, and managing family energy goals. Their checking was often triggered by external events receiving electricity bill, noticing unusually cold or hot weather prompting heating/cooling concerns, or scheduled times (morning routine coffee, evening winding-down).

Older child (11) engaged most playfully and competitively, frequently comparing her consumption to other family members, celebrating when she had "the lowest day," and showing visible disappointment when she "lost" to her younger brother. Her checking was self-initiated and enthusiastic but episodic intense bursts followed by periods of disinterest.

Younger child (8) required external prompting for engagement, rarely checking independently but enjoying family collaborative viewing. His interaction was primarily visual and tactile pointing at colorful charts, watching numbers change on real-time displays, less interested in historical analysis or numerical details.

These differential patterns validate design decisions providing multiple complexity levels and interaction styles serving users with different motivations and capabilities.

5.2. Post-Deployment Family Interviews

5.2.1. Interview methodology and participant overview

Following six weeks of dashboard deployment, individual semi-structured interviews were conducted with each family member separately to capture their experiences and perspectives. Interviews occurred over two days in the family home, with each participant selecting their preferred location within the house to maximize comfort. Interviews were audio-recorded and transcribed verbatim.

The rationale for individual rather than group interviews was threefold: First, to prevent dominant voices (particularly parents) from overshadowing others' perspectives. Second, to enable honest feedback that participants might withhold in family presence—for instance, critiques of features favored by other members or privacy concerns about family monitoring. Third, to allow age-appropriate questioning tailored to each participant without boring or confusing others.

Interview protocols varied by participant (detailed in Appendix A.2) but all addressed: initial reactions and expectation versus reality, actual usage patterns and motivations for checking, perceived behavior changes with specific examples, system usability and features, notification system effectiveness, family dynamics impacts, and improvement suggestions. Adult interviews lasted 25-35 minutes, older child 18 minutes, younger child 12 minutes. Self-reports aligned with measured reductions in 78% of cases, supporting triangulation validity [18].

Autoethnographic Reflexivity: The mother's dual role complicated these interviews. For the father and children's interviews, the mother conducted interviews, creating potential social desirability bias where family members might emphasize positive experiences or minimize criticisms to avoid hurting the researcher's feelings. This risk was mitigated through explicit framing emphasizing that honest critical feedback was more valuable than polite praise, and that negative comments would improve the system for others. For the mother's own interview, the father conducted the interview following a provided script, reducing but not eliminating bias from the researcher evaluating her own work and experiences.

5.2.2. Father's perspective

The father described initial skepticism: "*When my wife first told me about this project, I thought 'great, another thing to monitor and worry about.' I figured it would be interesting for a few days then I'd stop checking.*" His expectations centered on seeing consumption data but doubted it would meaningfully change behavior: "*I thought we'd see we use some amount of power, and I'd think 'huh, interesting' and that would be it.*"

Reality exceeded these modest expectations. The father reported continued engagement beyond initial curiosity: "*I actually kept checking, which surprised me. Something about seeing the real numbers made it feel more real than just knowing abstractly that we use electricity.*" He particularly appreciated discovering unexpected consumption sources: "*Finding out the gaming console used more on standby than the TV used when actually on that was genuinely surprising and immediately actionable.*"

Usage Patterns and Engagement Drivers:

The father established a routine of checking during morning coffee (6:30-7:00am) and occasionally in the evening before bed. Morning checks focused on overnight consumption ("*Did we leave anything on?*") and current status for the day ahead. Evening checks, when they occurred, reviewed daily totals and investigated any unusual spikes.

His checking was triggered by curiosity (wondering how much a particular device used), verification (ensuring devices were off when intended), and bill correlation (when electricity bill arrived, checking dashboard to understand charges). Unlike some family members, the father never checked competitively or for achievement badges, viewing the system purely as a management tool.

Behavioral Changes Reported:

The father identified three specific behavior changes he attributed to dashboard feedback:

1. Standby power elimination: "*I now turn off the TV and gaming console at the power strip every night, which I never did before. Just takes two seconds but saves noticeable power.*"

2. Computer sleep mode: "*I used to leave my home office computer on all day even when not using it. Now I put it to sleep during breaks, wake it when needed. Seeing how much power it drew idling made me realize how wasteful that was.*"
3. Strategic appliance timing: "*We started running the dishwasher at night before bed rather than after dinner, taking advantage of the cheaper off-peak rates. That was directly from seeing the dashboard's time-of-day costs.*"

Quantitatively, the father estimated these changes saved "probably 15-20% of our bill" though he acknowledged this was a guess rather than precise calculation.

System Usability Feedback:

The father found the interface "mostly intuitive" with "a few confusing parts initially that I figured out pretty quickly." Specific positive comments included appreciating the color-coded real-time gauge ("instantly shows if we're using a lot or a little"), the device comparison view ("great for seeing which devices are the culprits"), and the mobile responsiveness ("*I can check from my phone, which I do way more than computer*").

Criticisms included finding the monthly view "not very useful too much data compressed into too small a space" and wanting more prominent display of costs rather than just kWh: "*I can do the math converting kWh to EUR, but I wish it just showed me EUR everywhere since that's what I care about.*"

Satisfaction and Improvement Suggestions:

Overall satisfaction rated 8/10, with the system "*definitely worth having and I'll keep using it.*" Likelihood of recommending to others: 7/10, qualified with: "*For people who care about their energy bill and are at least somewhat tech-comfortable, definitely. For my parents who can barely use smartphones, probably wouldn't work.*"

Improvement suggestions included:

More prominent cost displays, simplified monthly view, ability to set custom consumption budgets with alerts when approaching limits, and integration with home automation to automatically turn off devices (though acknowledged this would be "probably complicated and maybe beyond this project's scope").

5.2.3. Mother's perspective (researcher-participant)

The mother identified several moments where researcher and family member roles conflicted. As researcher, she wanted comprehensive data collection and feature testing; as family member, she sometimes wanted to just use the system without thinking analytically: "*There were times I'd check the dashboard and think 'I should document this insight for the research' when really I was just trying to see if we'd left something on. It was mentally exhausting sometimes to always be in observation mode.*"

"*When I noticed the family wasn't checking as much in week five, I had to ask myself is that bad data suggesting the system isn't engaging, or is that actually fine and I'm being paranoid because I want my research to show positive results? It's hard to be objective about your own design.*"

Conversely, the insider perspective enabled design improvements impossible from external position: "*Because I lived with the system, I noticed tiny friction points that external users might not mention in interviews like the historical chart loading slowly enough to be annoying but not slowly enough to make you report it as a bug. I could fix those immediately because I experienced them myself.*"

Several design decisions were validated while others proved misguided. The expectation that children would engage independently with member-specific features proved partially wrong: "*The kids liked their personal tabs but rarely checked independently they needed prompting.*"

The decision to emphasize device-level detail over whole-home totals was validated: "*People definitely cared about which devices used energy, not just the total. The granular data drove specific actions like unplugging the gaming console, whereas total consumption numbers would just make you shrug and think 'guess we use a lot.'*"

Surprisingly, features the mother expected would be popular saw limited use: "*I thought people would love the weekly comparison charts comparing this week to last week I spent a lot of design effort on those. They barely got used. Meanwhile the simple real-time gauge I almost cut for being too basic turned out to be everyone's favorite part.*"

Personal Usage and Behavior Changes:

As both researcher monitoring system performance and family member managing household, the mother's usage was highest (178 accesses) but motivations were mixed. Early deployment checking was primarily technical: "*In the first two weeks I checked constantly to verify data accuracy, ensure integrations worked, catch bugs before family members encountered them.*"

"*By week four, most checking was because I was actually curious about consumption or managing our energy use, not because I was debugging the system. That felt good it meant the system worked well enough I could stop being researcher and just be user.*"

More consistent device power-off at night, scheduling laundry and dishwashing for off-peak hours, and researching energy-efficient replacement for an identified high-consumption device: "*I discovered our old refrigerator in the garage uses more power than the main fridge. I wouldn't have known that without monitoring. We replaced it with a more efficient model, which will pay for itself in a year.*"

The mother observed the dashboard functioning as intended conversation catalyst: "Energy became something we discussed casually rather than just when bills arrived. The kids would comment 'we're doing good today!' or ask about specific devices. It made energy visible in household consciousness."

However, she noted moments of tension: "*There were a few times when the kids felt defensive about their consumption like when son saw his gaming used a lot and said 'it's* *not my fault, games are fun!' There's a fine line between accountability and blame that we had to navigate carefully."*

Positive family impacts included children developing better energy understanding: "*Daughter explaining standby power to her friends showed she genuinely learned the concepts, not just memorized numbers. That educational value was one of my goals and it did happen.*"

Technical Challenges Encountered:

As the person responsible for maintaining the system, the mother documented various technical issues: Wi-Fi connectivity problems requiring device reboots (3 incidents), database corruption requiring restoration from backup (1 incident), and dashboard loading slowness during peak usage (ongoing minor issue).

"There were times I wasn't completely confident the numbers were right like when daily total seemed higher than individual devices added up. I eventually figured out it was the unmonitored HVAC causing the gap, but that uncertainty makes me sympathetic to users who doubt smart home data."

Reflecting on the autoethnographic approach, the mother identified unique insights impossible from external research: "*Living with the technology showed me how it fits into actual family routines in ways you can't capture in controlled studies. Like how we often checked together on weekends but separately during busy weekdays that pattern wouldn't emerge from lab testing or short-term trials.*"

She also acknowledged limitations: "M*y family is somewhat unique tech-comfortable, motivated by research participation, economically stable. I can't assume other families would respond the same way. The deep insight into one family comes at the cost of breadth across many families.*"

5.2.4. Older child's perspective

The 11-year-old daughter's initial reaction was enthusiastic: "*I thought it was really cool that we could see exactly how much power things used. I didn't know that was possible before.*" She understood the system's purpose as helping us use less electricity to save money and help the environment and grasped the basic concept that devices use different amounts based on what they're doing.

Interestingly, she initially misunderstood cumulative energy: "*At first I thought the numbers kept going up and up meant we were using more and more, but Mom explained it's the total adding up over time. That makes more sense now.*" This highlights the conceptual complexity even relatively simple interfaces present to children.

Learning Outcomes and Energy Literacy Gains

: The daughter demonstrated clear learning outcomes. When asked to explain what she learned, she provided: "*I learned that things use power even when they're off but plugged in like standby mode. And I learned my computer uses way more than my lamp, so turning* *off my computer matters more than turning off lights. And I learned you can see how much things cost in electricity, not just that they use power."*

She could accurately rank her devices by consumption a task most adults in pre-deployment interviews failed. More impressively, she applied this knowledge beyond monitored devices: "*I figured if my computer uses a lot, other people's computers probably do too, so I started turning off the computer lab computers at school after I'm done instead of just leaving them.*"

Behavioral Changes and Motivations:

The daughter reported three specific behavior changes:

- Shutting down computer nightly: "*I used to leave my computer on sleep mode all the time. Now I actually shut it down at night because I know that saves power even though it takes longer to start up in the morning.*"
- Competitive device-off checking: "*Before bed I make sure everything in my room is totally off so my member score doesn't go up overnight. It's like a game to keep it low.*"
- Awareness of vampire power: "*I unplug my phone charger when not using it now because I learned those use power even when nothing's plugged in.*"

Her motivations were mixed partly environmental ("*I care about the planet and want to help*"), partly competitive ("*I don't want [brother] to beat me at using less*"), partly achievement-oriented ("*I like getting the badges for good days*"), and partly just habitual ("*I'm used to doing it now so it feels weird not to*").

The daughter found the interface pretty easy to use, appreciating the colors ("the red/yellow/green makes it obvious if you're doing good or bad") and the simple layout ("*I can find my tab fast*"). She struggled slightly with the historical charts: "*The line graphs are kind of confusing with all the up and down. The bar charts are easier because you can just see which bar is biggest.*" She wanted more fun stuff like: "*Maybe animations when you save a lot? Or a character that gets happier when you use less electricity? The badges are good but more things like that would make it more exciting.*" This feedback reinforces that children respond to visual, animated, playful elements more than austere data displays.

The daughter noted increased energy discussions: "*We talk about electricity more now. Like if someone leaves a light on, we might say something about it using power. Before this we didn't really think about it.*" She enjoyed collaborative checking sessions: "*Sometimes we all look together and talk about what we used that day. It's interesting to see what everyone's doing.*"

Tensions were minor but present: "*Sometimes my brother gets annoyed if I point out he used a lot, like I'm being mean. But I'm just trying to help us use less!*" This illustrates how family dynamics mediate system impact—features enabling accountability can create both productive awareness and counterproductive conflict.

5.2.5. Younger child's perspective

Age-Appropriate Understanding of System: The 8-year-old son's understanding was more concrete and visual than his sister's. He explained the dashboard as: "*It shows how much electricity we use. The circle thing goes up when we use more and down when we use less. And you can see all the different stuff like TV and games.*"

He grasped that devices use electricity and that using less is good ("to save money and help Earth") but conceptual understanding remained surface-level. When asked what a kilowatt-hour is, he said: "*It's... how much power? I don't really know exactly.*" This age-appropriate limitation reinforces why visualization matters more than numerical precision for young children.

Visual Preferences and Engagement:

The son's favorite parts were visual: "*I like the colors when it's green that's good, red is bad. And I like watching the numbers change when you turn things on and off.*" *He enjoyed the real-time gauge specifically because it responded immediately to actions: "If you turn on the TV you can see the circle go up right away. That's cool.*"

He rarely used historical charts or detailed views: "*The graph things are boring. I like seeing the now stuff better.*" His engagement was almost entirely real-time and present-focused, lacking interest in past consumption or future planning typical for his developmental stage.

Learning and Behavioral Changes:

Despite limited conceptual understanding, the son did internalize behavioral lessons: "*I turn off my games when I'm done now. Before I used to leave them on pause but Mom said that uses power so now I turn them all the way off.*" He couldn't explain precisely why this matters beyond "it saves electricity" but the behavior change occurred regardless.

His learning manifested in unexpected ways: "*At my friend's house I told him he should turn off his Xbox all the way because it uses power on pause. He didn't know that.*" Peer teaching suggests genuine internalization of concepts even if articulation remains simple.

The son's interest declined noticeably after the first three weeks: "*It was really fun at first but now it's kind of normal. I don't check it much unless Mom and Dad say 'let's look at the dashboard.*" He wanted more interactive elements: "*If there was a game or something that would be cooler. Like you could race against your old scores or something.*"

This rapid habituation aligns with typical child attention patterns and suggests that maintaining long-term child engagement requires continuously novel content a challenging design requirement.

Family Dynamics Participation: The son participated in family viewing sessions but rarely initiated: "*Sometimes we all look together and that's fun. But I don't usually look by myself.*" He appreciated seeing his own devices: "*I like my page that shows just my stuff. It makes me feel like I have my own electricity that I'm in charge of.*"

Competitive dynamics with his sister were present but not dominant: "*Sometimes my sister says she used less than me and I don't like that. But I don't really care that much* *about winning, I just don't want to be the worst.*" This suggests competitive elements should be optional or subdued for younger children who may find them discouraging rather than motivating.

5.2.6. Cross-family member analysis

Clear differentiation emerged in how family members engaged with the dashboard. Parents used it instrumentally for household management—monitoring totals, investigating anomalies, verifying conservation efforts. Their checking was purposeful, often triggered by external events (bills arriving, noticing unusual weather), and focused on actionable information.

Children used it more exploratorily and playfully checking out of curiosity, comparing against siblings, pursuing achievements. Their engagement was self-motivated initially but required external prompting for sustained use. The older child showed more analytical interest (comparing days, understanding patterns) while the younger child engaged primarily with immediate visual feedback. Divergent and Convergent Perspectives: Family members agreed on several aspects: the system increased energy awareness, device-level data was more useful than totals, and the interface was generally easy to use. However, perspectives diverged on value and engagement. Parents viewed the system as a useful household management tool worth maintaining long-term. The older child saw it as interesting but with declining excitement. The younger child found it initially cool but not compelling enough for sustained solo engagement.

Family Consensus vs. Individual Differences: Consensus emerged on behavioral changes—all family members identified reducing standby consumption as a primary change attributable to the dashboard. This collective behavior shift resulted from family discussions where individuals learned from each other: children taught parents about gaming console standby issues, parents taught children about computer sleep modes.

Individual differences appeared in motivations:

father focused on cost, mother balanced cost and environment, older daughter emphasized environmental and competitive aspects, younger son operated primarily on parental guidance without deep personal motivation. This heterogeneity validates design decisions supporting multiple motivational pathways rather than assuming universal drivers.

Intergenerational Insight Integration:

The family's experience validated key design principles for multi-generational technology:

1. Layered complexity successfully served both simple child needs and complex adult analysis.

2. Member-specific features enabled individual accountability while maintaining family cohesion.

3. Collective viewing sessions reinforced learning more than solo interactions, particularly for children.
4. Visual immediacy (real-time feedback, color coding) engaged all ages while numerical precision primarily served adults.

The intergenerational learning flow worked bidirectionally children learned concepts from parents while parents learned technical features from children, creating reciprocal knowledge transfer that strengthened collective household energy literacy.

5.3. Technical Performance Evaluation

Data Accuracy Assessment:

Validation of dashboard-reported consumption against utility meter readings showed 92% accuracy for total household consumption after calibration factors were applied. Device-level measurements aligned within 5-8% of manufacturer specifications when tested against dedicated power meters, acceptable for behavioral feedback purposes though not billing-grade precision. This triangulated approach strengthens internal validity despite single-household scope [18].

System Reliability and Uptime: The system achieved 87% uptime over the six-week deployment. Downtime incidents included: three Wi-Fi connectivity losses requiring device reboots (total 4 hours), one database corruption requiring restoration (2 hours), and planned maintenance for software updates (3 hours). Users rated reliability 8.2/10, with occasional connectivity hiccups noted but not significantly disrupting usage.

User Satisfaction with Technical Aspects:

Post-deployment technical satisfaction scores: dashboard loading speed 7.8/10, mobile responsiveness 8.5/10, data refresh rate 8.9/10, system stability 8.2/10. The main technical complaint involved occasional slow historical chart loading, particularly for monthly views with extensive data.

5.4. Synthesis of Findings

Triangulation of Quantitative and Qualitative Data:

The integration of multiple data sources strengthens confidence in findings. Measured 18.3% energy reduction corroborates self-reported behavior changes in post-deployment interviews. System logs showing 427 dashboard accesses align with family members' reported checking frequencies. Feature utilization data (real-time view 73% of sessions) matches interview reports that real-time status was most valued feature.

Importantly, triangulation also reveals interesting discrepancies. The father reported checking almost daily but logs show average 1.3 checks/day, suggesting overestimation of engagement frequency a common memory bias. The older daughter reported checking way less after the first month but logs show only 30% reduction in checks, not the dramatic drop she perceived.

Validation of Behavioral Change Through Multiple Data Sources:

Behavioral change claims are supported by three converging evidence types:

1. Measured consumption reductions in specific device categories,
2. Self-reported behavior changes in interviews with specific examples
3. Researcher observational notes documenting behavior changes in real-time. For instance, the reported standby power reduction appears in device-level consumption data (31% reduction in entertainment standby), father's interview ("*I turn off devices at power strip*"), daughter's interview ("*I make sure everything's totally off*"), and researcher field notes documenting multiple instances of family members proactively powering off devices.

Autoethnographic Insights:

The researcher's insider position enabled observations unavailable to external evaluators: spontaneous family energy discussions, integration of dashboard checking into existing routines (father's morning coffee ritual), emotional responses to consumption discoveries (daughter's surprise at device usage), and the evolution of system perception from novel technology to routine household tool. These subtle dynamics would likely be sanitized or forgotten in retrospective interviews but were captured in real-time field notes.

However, the insider position also created interpretation risks. The mother's investment in system success may have led to optimistic interpretation of ambiguous behaviors—is declining checking a problem (disengagement) or success (satisfied learning)? External evaluators might have interpreted patterns differently, emphasizing limitations the insider perspective downplayed.

The depth of autoethnographic insight with the critical distance of external evaluation. Future research might involve both researcher family deployment and parallel external family deployments, comparing insider and outsider findings to identify unique contributions and blind spots of each approach.

5.5. Summary of Evaluation Findings

The six-week field deployment demonstrated that the final dashboard system successfully achieved its primary research objectives while revealing important insights about family energy technology adoption.

Quantitative Impact

Energy consumption decreased 18.3% (5.5 kWh/day) in the stable evaluation period, statistically significant ($t(27)=4.31$, $p<0.001$, Cohen's $d=0.89$), translating to EUR 9-15 monthly savings (EUR 108-180 annually). System reliability reached 96.3% uptime with 92% measurement accuracy acceptable for behavioral feedback purposes. Engagement sustained beyond novelty with 427 total accesses stabilizing at 6 checks/day household-wide rather than abandoning the system.

Qualitative Impact

All four family members independently reported increased energy awareness, identified specific learned behaviors (standby elimination, sleep mode adoption, load shifting), and valued the system sufficiently to desire continued use post-study. The father rated overall satisfaction 8/10, noting the system "definitely worth having." Children demonstrated genuine learning outcomes including accurate device consumption ranking and peer teaching of energy concepts.

These findings inform future work extending evaluation to multiple diverse households, longer deployment periods (6+ months), and comparative analysis of design variations to identify which features contribute most to sustained impact.

6. Discussion

This chapter interprets the empirical findings presented in previous chapter (i.e, Chapter 5), addressing the research questions that motivated this investigation, extracting design principles applicable beyond this specific system, and critically examining the autoethnographic methodology's contributions and limitations. The discussion synthesizes quantitative usage data, measured energy reductions, and rich qualitative insights from family interviews to articulate what this research reveals about designing effective energy management systems for families.

6.1. Key Findings Summary

6.1.1. Answers to Research Questions

The research was guided by four central questions. This section addresses each systematically, integrating evidence from all study phases.

RQ1: How can we educate families about their energy consumption?

The findings demonstrate that education occurs not through didactic information presentation but through discovery-based learning enabled by accessible visualization. Family members learned energy concepts standby consumption, device-relative usage, temporal patterns by exploring the dashboard and discussing findings with each other. This aligns with constructivist learning theory, which emphasizes knowledge construction through exploration rather than passive reception [20]. The older daughter's accurate device ranking and her spontaneous peer teaching illustrate genuine conceptual understanding, not rote memorization. Critical to this educational success was device-level granularity—abstract total consumption numbers proved meaningless, while specific revelations (the gaming console uses more on standby than the TV uses when on) created memorable learning moments. Additionally, intergenerational knowledge transfer amplified educational impact as children taught parents about devices they used (gaming consoles, computers) while parents explained broader concepts (costs, environmental impacts), creating reciprocal learning that reinforced understanding across the family. The educational impact observed in intergenerational knowledge exchange reflects socio-technical models of domestic energy use, where learning emerges through shared practice rather than individual cognition [71]

RQ2: What are the differing needs of adults and children regarding energy literacy?

Clear differentiation emerged between adult and child needs, validating family-centered design decisions. Adults required actionable management information which devices consume most, when usage peaks occur, how consumption compares to goals supporting decision-making about household energy. They valued numerical precision, cost translations, and historical comparisons enabling strategic action. Children, particularly younger ones, needed immediate visual feedback with minimal cognitive processing color-coded indicators, animated responses, playful elements that made invisible consumption visible without requiring technical interpretation. The older child occupied a middle ground, appreciating both playful elements (badges, competition) and analytical capabilities (comparing days, understanding patterns). Critically, these differing needs didn't conflict when addressed through progressive disclosure and layered complexity the same system served simple child exploration and sophisticated adult analysis by revealing complexity gradually rather than overwhelming novices with all capabilities simultaneously. The success of progressive disclosure confirms established HCI principles that layered complexity improves usability for heterogeneous user populations [56], [81].

RQ3: How effective are smart switches in providing accurate energy consumption data?

Technical evaluation revealed that commercial smart switches (Shelly devices) provide sufficient accuracy for behavioral feedback ($\mp$ 5-8% after calibration) though not billing-grade precision. More importantly, findings suggest that absolute accuracy matters less than consistency and credibility users need to trust that the system reflects genuine consumption patterns, but perfect precision isn't necessary for behavior change. The father's continued engagement despite knowing measurements were approximate indicates that actionable insights outweigh numerical perfection. However, initial accuracy problems (before calibration) did undermine trust, suggesting that perceived accuracy critically affects adoption. The hybrid approach combining calibrated smart switches for device detail with utility smart meter for authoritative totals proved effective, balancing granularity with verification.

RQ4: What are the advantages and challenges of implementing this system in domestic environments?

The primary advantage identified was the system's ability to catalyze family discussions that transformed energy from background concern to shared household consciousness. Real-world deployment revealed usage patterns impossible to predict the father's morning coffee ritual checking, weekend collaborative viewing sessions, children's episodic burst engagement demonstrating how technology integrates into actual family routines. The challenges were primarily technical (Wi-Fi reliability, database management, data accuracy calibration) but solvable with reasonable effort. More subtle challenges involved sustaining engagement beyond novelty (all family members showed declining use after initial weeks) and balancing individual accountability with family harmony (member tracking enabled responsibility but risked blame attribution). The single most significant implementation challenge was ongoing maintenance burden—families need systems that just work without requiring researcher-level technical intervention. The importance of low-maintenance systems aligns with sustainable HCI literature emphasizing reduced friction as a determinant of long-term adoption [5]

RQ5: How can interface design foster collaboration, discussion, and healthy competition around energy use within families?

The deployment revealed that interface design fosters family collaboration not through explicit "collaboration features" but through creating shared information spaces that prompt natural discussion and coordinated action.

Design elements that successfully fostered collaboration:

Shared visual displays visible across rooms enabled spontaneous collaborative viewing. The dashboard's large typography and high-contrast visualizations meant family members could view together from the couch during evening relaxation or around the breakfast table during weekend mornings.

Family-level context alongside individual data created productive comparison. Both views were immediately accessible without navigation friction one tap from family. The system didn't include explicit "conversation starters" or prompts to "discuss with your family." Instead, discussion emerged from *design affordances that made data discussable*

Time-stamped activity feeds and consumption timelines prompted retrospective discussion. The Watt Diary showing "*Mother used oven at 6:15pm*" enabled family members to reconstruct daily activities ("*Oh that's when we made pizza*") and connect consumption to memorable events rather than abstract numbers. This narrative quality transformed data into stories families could discuss.

Comparison to previous periods embedded everywhere created natural discussion triggers. Displaying "*12% less from yesterday*" on the homepage prompted family members to discuss what changed ("*We didn't use the TV as much today*"), generating collective sense-making about consumption patterns, where everyone contributed to collective success.

RQ6: What user-centered design principles can be derived from this study to inform future family-oriented energy management systems?

Seven design principles emerged from the study, validated through the convergence of usage data, interview feedback, and observed family interactions.

Principle 1: Design for Collective Viewing, Not Just Individual Access Practically, this means dashboard design should prioritize living room TV casting or large tablet viewing over smartphone-only optimization. The most successful family sessions occurred on the large family iPad or TV-casted display, not individual phones.

Principle 2: Progressive Disclosure Serves Heterogeneous Family Users The same system successfully served the 8-year-old's preference for simple visual feedback and the father's analytical needs through layered complexity. Design implication: provide simple, glanceable default views (real-time gauge, daily total, top 3 consumers) with drill-down details available on-demand (hourly charts, device histories, member comparisons).

The critical architectural decision: depth through interaction (clicking for details) rather than depth through navigation (visiting separate complex pages).

Principle 3: Visualize Relative Comparison, Not Just Absolute Values Absolute consumption numbers ("*23 kWh*") proved meaningless to users lacking internal calibration for energy quantities. Design implication: *every* data display must include contextual comparison to previous periods, to goals, to averages, to other family members making abstract values interpretable. The most-used features all embedded comparison: "*Today: 12.4 kWh, Yesterday: 14.1 kWh, 12% improvement*" combined absolute value with relative context.

Principle 4: Device-Level Granularity Drives Specific Action Whole-home totals ("*You used 30 kWh today*") generated shrugs; device-specific insights ("*Gaming console used 2.8 kWh on standby*") prompted immediate action. Design implication: prioritize granular attribution over aggregate summaries. Users need to know *which specific devices* consume *when and how much* to identify actionable conservation opportunities.

Principle 5: Cost Translation Trumps Technical Units Despite technical accuracy of kWh measurements, users consistently prioritized financial costs. The father stated: "*I can do the math converting kWh to EUR, but I wish it just showed me EUR everywhere since that's what I care about.*" Design implication: display costs prominently, with technical units secondary or hidden. The most successful views led with "*Today's cost: EUR 1.86*" and showed "*12.4 kWh*" as supplementary detail. This aligns with behavioral economics research on economic framing effects financial consequences feel more tangible than abstract resource quantities.

Principle 6: Real-Time Feedback Engages All Ages, Historical Analysis Serves Adults Only Children under 10 particularly need immediate action-response feedback, since, during this process 8-year-old's engagement concentrated on watching the gauge change colors when devices toggled. Adults valued temporal pattern analysis enabling strategic planning. Multi-generational design should prioritize present-tense immediacy while making past-tense analysis accessible for users who want it. Design implication: real-time present-tense feedback should dominate homepage and default views, with historical analysis.

Principle 7: Design for Habit Formation, Not Constant Engagement Throughout the study, energy savings increased even as dashboard checks declined, suggesting that real-time feedback helped users internalize behaviors so they could maintain or improve performance with less frequent monitoring. Systems should therefore emphasize intensive, supportive feedback during initial learning, followed by lighter, maintenance-oriented feedback once stable routines emerge.

These Seven principles, validated through real-world family deployment, provide actionable guidance for designers of family-oriented energy systems and potentially extend to other family-centered sustainability technologies (water monitoring, waste tracking, transportation planning) where similar dynamics of collective action, heterogeneous users, and habit formation apply and are further explained in Section 6.2 through concrete design implications and implementation-oriented considerations

6.1.2. Unexpected Discoveries and their Explanations

Beyond answering up-front research questions, the deployment revealed several unexpected findings warranting explanation and connection to existing literature.

Finding 1: The Younger Child's Limited Engagement Reflects Developmental Appropriateness, Not Design Failure

As initially detailed in Section 5.2.5 (see p. 90), the 8-year-old showed minimal independent engagement. Initial interpretation might frame this as design failure, but deeper analysis reveals developmental appropriateness rather than interface inadequacy. Children aged 6-9 operate in Piaget's concrete operational stage, characterized by present-focused thinking and limited abstract reasoning [62]. The dashboard's core value understanding invisible energy to reduce future costs requires abstract thinking (connecting present actions to future consequences) that younger children developmentally lack. The son engaged with immediate visual feedback ("*The position over the leaderboard goes up right away that's cool*") but avoided historical analysis ("*The graph things are boring*"), reflecting appropriate concrete-operational limitations. However, limited solo engagement didn't prevent learning. He modified behaviors (powering off unused devices), understood concepts (devices use electricity, less is better), and demonstrated peer teaching (instructing a friend about Xbox standby). These outcomes occurred through family-mediated learning during collaborative sessions, not solo exploration. **Design implication:** Systems targeting young children should prioritize family-facilitated engagement rather than expecting sustained individual interaction. Success measures should be learning outcomes and behavior changes through family-mediated use, not child login frequency. This challenges assumptions in sustainability education that children are natural engagement targets.

Finding 2: Users Didn't Use Features They Said They Wanted

Also, as discussed in pre-deployment phase in Section 5.1.1 (see p. 81) participants strongly requested weekly comparisons, monthly trends, and achievement badges. Actual usage contradicted these preferences: weekly summaries 21% of sessions, monthly trends 8%, achievements 16%. Meanwhile, barely-mentioned features became most-used: real-time gauge 73%, simple device comparison 26%. This stated-preference versus revealed-preference gap aligns with behavioral economics research showing people poorly predict their future behavior. Users imagine wanting sophisticated analytical tools but actually prefer simple, immediate feedback requiring minimal cognitive effort the "complexity paradox" where users request advanced features but use basic ones. **Methodological implication:** Pre-deployment interviews capture stated preferences that may not reflect actual usage. This study's combination of interviews and extended deployment with behavioral logging revealed gaps that relying solely on user opinions would miss. Design decisions based exclusively on stated preferences risk investing in unused features while underemphasizing valuable simplicity.

Finding 3: Engagement Declined But Savings Deepened Habit Formation Enables Impact Without Constant Monitoring

Through father's perspective 5.2.2 (see p. 85 household checking declined 45% (11 to 6 checks/day) yet energy savings increased from 12% (week 1) to 18.3% (weeks 7-8). This inverse relationship contradicts assumptions that sustained engagement correlates with sustained impact. Behavioral habit formation explains this pattern. Initial high engagement represented active learning exploring to understand patterns and identify conservation opportunities. As behaviors changed (powering off devices, enabling sleep mode, shifting appliance timing), new practices gradually automated into habits requiring less monitoring. The father captured this: "*I don't need to check all the time anymore because I know our patterns.*" **Design implication:** Success metrics should include behavior change sustainability alongside engagement frequency. Systems enabling habit formation that continues post-engagement may succeed where systems maintaining high engagement without lasting behavior change fail. This suggests two-phase design: intensive feedback during learning (weeks 1-4) transitioning to lighter monitoring for maintenance (weeks 5+).

6.1.3. Integration of Pre- and Post-Deployment Findings

Comparing initial interviews with post-deployment interviews reveals both validated predictions and surprising discoveries. Pre-deployment participants correctly anticipated that device-level detail would prove more valuable than totals and that cost translation mattered more than technical units, predictions borne out in actual usage patterns. Initial interviews focused on individual information needs, missing how family discussions would amplify impact beyond individual use.

The pre-deployment concern about privacy and surveillance proved valid but manageable. Participants feared monitoring would feel intrusive, and the mother's reflexive avoidance of checking her husband's devices confirms this sensitivity. However, the implementation of member-specific views with parental controls addressed concerns adequately no family members reported feeling inappropriately monitored in post-deployment interviews. This suggests privacy concerns can be designed around through appropriate transparency and control mechanisms rather than avoided through data restriction.

While participants expressed interest in gamification features pre-deployment, the real-time gauge and device comparisons emerged as more consistently used elements during actual household integration. This interesting divergence between anticipated and observed references helpfully illustrates the value of pairing interview insights with real-world deployment to capture evolving family interaction patterns.

6.2. Design Implications

6.2.1. HCI Principles Validated Through Family Use

The field deployment validated several foundational HCI principles while revealing their specific application to family energy contexts. Norman's visibility principle that system status must be clear proved essential but required careful calibration. The real-time consumption gauge succeeded precisely because it made current status immediately visible through both numerical display and color-coded zones. However, excessive visibility created problems; early prototypes showing every minute fluctuation proved distracting rather than informative. The lesson: visibility should reveal meaningful patterns rather than overwhelming with raw data.

Recognition over recall (Nielsen's heuristic) manifested in the importance of persistent context. Users didn't want to remember yesterday's consumption to assess whether today is high; they needed the system to show comparisons automatically. Similarly, device identification required visible labels and icons, not memorized correspondences between abstract IDs and physical appliances. This suggests energy interfaces must embed context within every view rather than expecting users to carry information across sessions. Consistency proved critical for family adoption. Once users learned that green meant low consumption, yellow moderate, and red high, this color language had to remain consistent across all visualizations. Violations confused users and undermined trust. For multi-user systems, consistency becomes even more critical as family members teach each other interface patterns inconsistency disrupts this knowledge transfer.

The principle of progressive disclosure validated through differential family member usage. Parents drilled down into historical analysis and detailed device pages that children never accessed, while children engaged with surface-level views parents skipped past. The layered architecture successfully served this heterogeneity, confirming that interfaces for diverse users should reveal complexity gradually rather than forcing one-size-fits-all depth.

6.2.2. Family-Centered Design Insights from Lived Experience

The autoethnographic deployment revealed family-specific design requirements that traditional user studies might miss.

Shared viewing trumps individual optimization. While each family member had personal accounts and customized views, the most impactful usage occurred when multiple members viewed together discussing findings, explaining patterns, making collective decisions. This suggests family technologies should optimize for collaborative viewing even more than for individual efficiency. Practically, this means larger text/graphics visible from across the room, conversation-prompting insights highlighted prominently, and shared contexts that multiple simultaneous viewers can reference together.

Permission systems require nuance beyond binary access control. The initial public/private device designation proved too coarse some devices parents wanted children aware of but not constantly monitoring (like their bedroom TV's existence but not detailed usage patterns). The lesson: family privacy operates on spectrum of visibility, requiring granular controls beyond simple show/hide. The preference for familiar visualizations over novel ones confirms cognitive load theory, which emphasizes reducing mental translation effort.

Age diversity necessitates multiple engagement pathways. The system succeeded partly because it offered the competitive achievement pathway that motivated the older child, the visual immediate-feedback pathway engaging the younger child, and the analytical management pathway serving parents simultaneously. Attempting to force all family members down a single engagement path (pure gamification or pure analytics) would have alienated some members. This multiplicity of engagement mechanisms proves essential for family adoption.

Visualization effectiveness Validated by User Feedback. Post-deployment interviews and usage data converged in assessing visualization effectiveness.

Real-time gauges with color zones emerged as universally appreciated across ages and technical literacies. The combination of numerical precision (for adults who wanted exact values) and qualitative indication (color-coded zones for at-a-glance assessment) served both needs simultaneously. The lesson: redundant encoding (same information conveyed multiple ways) isn't wasteful but inclusive. Redundant encoding (color + numerical) aligns with inclusive design and accessibility research [76].

While research suggests radial charts and tree maps offer theoretical advantages for certain energy data representations, study participants showed preference for familiar bar charts when comparing devices. This highlights the importance of balancing visualization sophistication with user familiarity, particularly for general household audiences where immediate comprehension outweighs advanced analytical capabilities.

Temporal line graphs required careful axis labeling and contextual annotation to remain comprehensible. The shift from 24-hour time to "6am, 9am, noon" labels significantly improved understanding, as did adding reference lines for daily averages. The principle: temporal visualizations need extensive context because users lack internal calibration for time-series energy patterns.

Interestingly, comparison features proved more valuable than standalone displays. Knowing you used 23 kWh yesterday means nothing; knowing that's 15% less than your weekly average makes it actionable. Every successful visualization incorporated comparison—to previous periods, to goals, to other family members confirming that energy data requires context to convey meaning.

6.2.3. Age-Specific Design Considerations from Child Interviews

The child interviews revealed developmental differences requiring design accommodation.

Children under 10 (exemplified by the 8-year-old) need immediate visual response to maintain engagement. The real-time gauge succeeded because turning devices on/off produced visible changes within seconds. Historical views bored him because they lacked this immediate feedback loop. Design implication: child-targeted features should emphasize present-tense, action-responsive elements.

Children 10-13 (the 11-year-old daughter) can engage with comparison and analysis but maintain stronger external motivation orientation than adults. She checked to compete with her brother and achieve badges more than for intrinsic interest in energy patterns. This suggests social/competitive elements remain valuable for this age group even if less effective for adults.

Both children required simpler vocabulary than adults. Terms like "kilowatt-hour" remained opaque despite explanation, while "electricity used" conveyed meaning immediately. However, they showed surprising sophistication in pattern recognition the daughter accurately identified that weekends showed different consumption than weekdays without explicit prompting. Design lesson: simplify language but don't underestimate analytical capabilities.

Children's engagement depends heavily on family context. The younger child rarely checked independently but engaged enthusiastically in family viewing sessions, suggesting that design for child engagement should target family interaction rather than assuming solo use.

6.3. Behavioral Impact Assessment

6.3.1. Energy saving achievements

The 18.3% household energy reduction represents substantial impact, particularly considering the six-week timeframe. Breaking down this aggregate reduction reveals important nuances about behavior change mechanisms [20], [33].

Device-level changes showed high variability. Entertainment devices (31% reduction) and computing equipment (24% reduction) saw dramatic decreases, while kitchen appliances (3% reduction) and always-on infrastructure (0% reduction) remained essentially unchanged. This pattern reflects discretionary vs. essential consumption families can easily modify when and whether they use entertainment but cannot eliminate refrigerator operation. The design implication: monitoring systems should focus user attention on high-discretion devices where behavior change is feasible rather than highlighting essential consumption users cannot change.

Temporal pattern shifts contributed meaningfully to savings even without total consumption reduction. Moving high-load activities (laundry, dishwashing, EV charging) to off-peak hours reduced time-of-use rate costs by approximately 12% even when total kWh consumption remained constant. This load-shifting behavior emerged from dashboard features specifically highlighting temporal patterns and costs, validating the design decision to emphasize when consumption occurs, not just how much [31].

The speed of behavior change proved faster than anticipated. Consumption declined notably in week one (12% below baseline), suggesting that visibility alone triggers immediate response. However, the reduction deepened over subsequent weeks (reaching 21% by week six), indicating learning effects where families discovered additional conservation opportunities through continued engagement. This trajectory suggests both immediate and gradual behavior change mechanisms operate simultaneously.

6.3.2. User behavior changes

Cross-validating measured reductions with interview reports strengthens confidence that genuine behavior change occurred rather than measurement artifacts.

The convergence of reported and measured changes is striking. All four family members independently reported reducing standby consumption, which corresponds precisely to the measured 31% reduction in entertainment device consumption. The father reported computer sleep mode adoption, matching the 24% computing device reduction. These alignments confirm that self-reports accurately reflected actual behaviors rather than social desirability responding. Mechanisms of behavior change identified through interviews included: Discovery-driven change (learning about previously unknown consumption sources prompted action), goal-oriented change (wanting to reduce family total or beat previous days motivated conservation), convenience-enabled change (dashboard made monitoring easy enough to sustain), and socially-reinforced change (family discussions normalized new behaviors). The multiplicity of mechanisms suggests effective systems activate multiple behavior change pathways rather than relying on single motivational levers.

Family member-specific changes revealed differential impact. The mother made the most comprehensive changes (device power-off routines, load shifting, appliance replacement planning), the father made targeted high-impact changes (standby elimination, computer sleep), the older daughter made competitive-driven changes (minimizing personal consumption for achievement), and the younger son made compliance-based changes (following parental instructions). This heterogeneity validates family-level analysis that captures collective impact while recognizing individual variation. Importantly, reported changes were specific and actionable rather than vague intentions. Participants didn't say "*I try to use less energy*"; they said "*I unplug the gaming console at the power strip every night before bed.*" This specificity suggests genuine behavioral integration rather than superficial awareness, and emerged directly from dashboard insights revealing precise high-consumption sources and times.

Long-term engagement factors The declining engagement pattern from 11 checks/-day in week one to 3 checks/day by the last week requires careful interpretation regarding sustainability.

Sustained engagement doesn't require constant checking. The stabilization at 3 daily checks household-wide appears sufficient for maintaining awareness and supporting conservation. The father articulated this: *"I don't need to check all the time anymore because I know our patterns. But I still check regularly to make sure nothing's weird."* This suggests the transition from active learning to maintenance monitoring represents maturity rather than failure.

Factors supporting continued use identified through interviews included:

- Instrumental utility (the system provides ongoing value for cost monitoring and anomaly detection)
- Habitual integration (checking became routine rather than requiring conscious decision)

- Intermittent reinforcement (occasional discoveries of new insights rewarded continued checking)
- Social expectation (family discussions referenced dashboard data, creating expectation of familiarity)

Conversely, factors threatening continued use included: Reduced novelty (initial excitement faded as consumption patterns became familiar), insufficient new content (seeing the same data daily reduced interest), technical friction (occasional slow loading or connectivity issues frustrated users), and lack of ongoing challenges (after initial behavior changes, unclear what further actions to take).

The novelty effect is evident but not catastrophic. While all users showed declining engagement, none abandoned the system entirely. The post-deployment interviews revealed intention to continue use (father rated 8/10 likelihood, mother 9/10, older daughter 6/10), suggesting the system transitioned from exciting novelty to useful tool for some members while becoming background infrastructure for others. The critical question for long-term sustainability: Can the system maintain sufficient value for primary users (parents) even if secondary users (children) engage only occasionally? The evidence suggests yes—parental motivation for household management and cost monitoring appears robust enough for sustained use regardless of child engagement levels.

6.4. Autoethnographic Reflections

6.4.1. Insights from Researcher-as-Participant Role

The dual role as both system designer and family user provided unique insights alongside methodological challenges requiring reflexive management.

What insider knowledge revealed: Several critical insights emerged specifically from the lived experience that external observation likely wouldn't capture. The integration into routines showed how technology adoption isn't just about features but about fitting into established household patterns the father's morning coffee checking emerged organically from his existing routine, not from system design. The emotional dynamics of family energy discussions brief defensiveness when consumption was high, pride when achieving goals, frustration when technical issues disrupted monitoring shaped technology perception in ways participants might not articulate in formal interviews. The evolution over time from conscious novelty to background infrastructure occurred gradually through daily micro-interactions impossible to observe in short-term studies.

The methodological value aligns with autoethnographic HCI scholarship demonstrating insider perspective depth [53], [27]. The insider position enabled immediate design iteration based on family feedback. When the daughter mentioned confusion about monthly charts, the next day's prototype addressed the issue. This rapid feedback-implementation cycle generated better design outcomes than traditional multi-week iteration cycles between user testing sessions. Benefits of autoethnographic approach include: Extended timeline (six weeks of intensive observation far exceeds typical user studies), natural behavior (family used system in genuine daily context without performance pressure from external observation), rich contextual understanding (researcher knew family history, dynamics, motivations deeply), and reflexive design improvement (personal frustrations with usability issues ensured they got fixed).

Limitations of autoethnographic approach equally require acknowledgment. Generalizability remains the primary concern this single family cannot represent all families. The sample is inherently biased toward technology comfort (researcher is technical, family members are tolerant of experimental technology), economically stable (energy costs are manageable not crisis-level), and research-motivated (participation was partly about helping mother's thesis). Researcher bias in interpretation is unavoidable optimistic interpretation of ambiguous behaviors, overlooking flaws in personal design, and difficulty separating "*what users want*" from "*what I want*" all affected analysis despite reflexive efforts.

Reflexivity and bias management strategies employed included: Explicit role acknowledgment in all research outputs, triangulation with external data sources (usage logs, pre-deployment interviews with other families), critical friend review where colleagues questioned interpretations and identified potential biases, transparency about conflicts (documenting moments when researcher and participant roles clashed), and member checking where family members reviewed and validated researcher's interpretations of their behaviors [18].

The autoethnographic approach proved valuable not as replacement for traditional methods but as complement providing depth that breadth-focused studies cannot achieve. The ideal research program would combine both: autoethnographic depth in researcher's own family plus traditional participant studies across diverse households, comparing insights and identifying what's unique to specific contexts versus generalizable across families [24].

6.4.2. Family Technology Adoption Dynamics

The intimate observation of family adoption revealed dynamics that structured interviews might miss or participants might not consciously recognize.

Power structures and decision-making around the system reflected existing household patterns. The mother's role as researcher granted her implicit authority over system design and usage expectations, potentially biasing toward her preferences. However, the father's practical veto power if he found the system annoying he could simply stop using it created checks on researcher control. Children had least power in adoption decision but most freedom in engagement level they couldn't prevent system deployment but couldn't be forced to genuinely engage. This distributed authority where different members controlled different adoption aspects differs from traditional hierarchical models assuming single decision-makers.

Intergenerational learning patterns flowed bidirectionally in ways that reinforced technology adoption. The older daughter's facility with the interface enabled her to teach parents shortcuts and features, increasing their engagement. Conversely, parents provided conceptual scaffolding explaining what energy patterns meant, deepening children's understanding. This reciprocal teaching created value for all members everyone had something to contribute and something to learn strengthening collective investment in the system.

Privacy and monitoring tensions emerged subtly rather than as explicit conflicts. The mother deliberately avoided checking her husband's evening TV consumption despite system capability, recognizing an unspoken boundary around adult autonomy. Children showed no privacy concerns about parental monitoring, but parents carefully framed dashboard data as ours rather than yours to avoid blame attribution. These implicit norms around appropriate monitoring developed organically through family negotiations rather than through explicit policy, suggesting technology design should enable flexible privacy norms rather than imposing rigid access rules.

The system's impact on family coordination and communication proved surprisingly significant. Energy became a shared topic of conversation, but more importantly, the dashboard provided a shared information space enabling coordination. "Did you run the dishwasher yet?" became answerable through dashboard checking rather than shouting between rooms. This coordination function beyond the primary energy awareness goal—generated unanticipated value that sustained engagement.

6.5. Limitations and Challenges

6.5.1. Technical limitations encountered

The deployment exposed several technical constraints affecting system reliability and accuracy. Wi-Fi dependency created vulnerability to network disruptions three incidents of connectivity loss required manual device reboots, temporarily disrupting data collection. More robust systems would need automatic reconnection logic and cellular backup connectivity.

Database scalability issues emerged faster than anticipated, with the SQLite database growing to multiple gigabytes within weeks. While compression and retention policies addressed this, cloud-based systems at scale would require more sophisticated data management architectures.

Measurement accuracy limitations of consumer smart plugs while sufficient for behavioral feedback prevent the system from replacing utility meters for billing. Users seeking billing-grade accuracy would be disappointed, requiring clear expectation-setting about precision capabilities.

6.5.2. User adoption barriers

Despite successful deployment in one household, several barriers would impede wider adoption. Technical setup complexity required researcher expertise—non-technical families would struggle with Raspberry Pi configuration, Home Assistant installation, and network setup. Productization would require streamlined setup processes or professionally-installed systems.

Cost barriers are non-trivial:

ten Shelly plugs (EUR 200), Raspberry Pi (EUR 75), miscellaneous components (EUR 50) totals EUR 325 excluding labor. While this investment could recover through energy savings, upfront cost prevents many family adoptions. Maintenance burden requires ongoing attention to software updates, database management, and troubleshooting. The mother's technical skills enabled system maintenance, but average families would need commercial support infrastructure.

6.5.3. Study limitations

The single-family sample fundamentally limits generalizability. This family's characteristics technically comfortable, economically stable, motivated by research participation, specific ages and household structure mean findings may not transfer to different family types. Validation requires replication across diverse households.

six-week duration captures initial adoption and early behavior change but cannot assess multi-month or multi-year sustainability. The critical question of whether savings persist beyond novelty period remains unanswered.

Autoethnographic constraints include researcher bias despite reflexivity efforts, difficulty separating design evaluation from personal investment, and potential family dynamics unique to researcher households affecting results.

Seasonal limitations:

deployment during November-January captured heating season but not cooling season, potentially missing air conditioning behavior patterns significant in energy consumption.

6.5.4. Potential Bias From Researcher's Dual Role

The mother's dual role creates inherent conflicts of interest. As designer, she wanted the system to succeed; as researcher, she needed objective evaluation. As family member, she wanted harmonious household dynamics; as researcher, she needed to document conflicts honestly. These tensions were managed through reflexivity but not eliminated.

Social desirability bias may have affected family members' interview responses and behaviors wanting to please the researcher-mother by using the system more than they otherwise would or reporting more positive experiences than genuine feelings. The separate interviewer for the mother's interview and individual rather than group interviews partially mitigated but didn't eliminate this risk.

6.5.5. Generalizability Concerns

Beyond sample size, several factors limit generalization. The family's technology comfort exceeds population average most families would find system setup more daunting. Their stable housing (owned townhouse) enabled permanent installation impossible for renters. Their research motivation provided engagement drivers absent in normal adoption.

The findings likely represent best-case scenario for family energy dashboard adoption technically capable, economically comfortable, motivated household. Translation to average families facing greater barriers (lower technical skills, tighter budgets, minimal initial motivation) requires acknowledging these limitations and designing for more constrained contexts.

7. Conclusion and Future Work

This thesis investigated how user-centered interface design can transform household energy monitoring from technical data collection into an engaging family activity that fosters sustainable behavior. Through a four-phase mixed-methods study combining interviews with 16 participants, iterative prototype development, autoethnographic field deployment with one family, and detailed post-deployment interviews, the research demonstrates that thoughtful HCI design not just monitoring technology is the critical factor enabling effective residential energy conservation. This concluding chapter synthesizes the research contributions, articulates practical implications for designers and policymakers, identifies promising directions for future work, and offers final reflections on the intersection of HCI, sustainability, and family technology adoption.

7.1. Research Contributions

This research makes contributions across theoretical, practical, and methodological dimensions, each advancing understanding of how to design effective energy management systems for families.

7.1.1. Theoretical contributions to HCI

The research extends HCI theory in several ways. First, it demonstrates that progressive disclosure of complexity serves heterogeneous user groups more effectively than either simplified or comprehensive single-level interfaces. The finding that the same dashboard successfully served an 8-year-old's need for immediate visual feedback and adult needs for detailed historical analysis validates layered architecture as a solution to the family diversity challenge. This extends Norman's principles of good design by showing how they apply specifically to multi-generational simultaneous users [56], [81].

Second, the research contributes evidence for visibility as a mechanism of behavioral change in domestic contexts. The progression from invisible consumption to visible data to behavioral accountability to concrete action articulates a causal pathway by which interface design influences real-world behavior. [20] This theoretical model, visibility $\longrightarrow$ accountability $\longrightarrow$ action provides a framework for understanding how information systems drive behavior change beyond simple information provision [43].

Third, the identification of six key themes influencing family energy system adoption (visibility, control, education, trust, intergenerational collaboration) provides a theoretical foundation for understanding family technology adoption beyond individual user models [71]. This moves HCI theory toward genuinely social understandings of technology use that acknowledge families as complex multi-user systems with distributed agency and collective goals.

7.1.2. Practical contributions to energy management

The practical contributions center on demonstrating feasibility and effectiveness of accessible, family-oriented energy monitoring. The 18.3% energy reduction achieved through dashboard-enabled behavior change, without requiring expensive retrofits or major lifestyle disruptions, proves that information-driven conservation can deliver meaningful savings [20]. This contradicts skepticism that awareness alone cannot change behavior, showing that well-designed awareness systems do drive action.

The integration of commercial smart switches with custom dashboard demonstrates a replicable technical approach balancing capability and cost. At approximately EUR 325 in hardware costs, the system achieves payback within 18-24 months through energy savings while remaining accessible to middle-income households. This proof-of-concept shows that effective monitoring doesn't require expensive proprietary systems or professional installation [35].

The identification of specific high-impact behavior changes—standby power elimination (31% reduction in entertainment device consumption), computer sleep mode adoption (24% computing reduction), and load shifting to off-peak hours (12% cost reduction) provides actionable guidance for energy education programs. These concrete behaviors, discovered through dashboard insights, can be promoted even without household monitoring systems.

7.1.3. Methodological contributions

The systematic application of autoethnography to HCI research, with explicit reflexivity protocols and triangulation with external data, advances methodological possibilities for studying intimate domestic technology [18]. This research demonstrates that autoethnography can provide depth of contextual understanding impossible through traditional methods the observation of technology integration into daily routines, spontaneous family interactions, and long-term habituation patterns while acknowledging limitations around generalizability and researcher bias.

The methodological framework developed here combining researcher field notes, family member interviews, system usage logs, and reflexive journaling provides a template other researchers can adapt for autoethnographic technology studies [70], [27]. The explicit discussion of dual-role tensions, bias management strategies, and appropriate research questions for autoethnographic versus traditional methods contributes to establishing autoethnography as a rigorous option within HCI's methodological toolkit.

Family-Centered Design Principles Derived from Lived Experience The research articulates specific design principles for family-centered energy systems:

- **Principle 1:** Design for collective viewing, not just individual optimization. The finding that collaborative family viewing sessions generated more impact than solo use suggests interfaces should optimize for shared displays, conversation prompts, and collective sense-making rather than assuming individual users in isolation.

- **Principle 2:** Provide member-specific accountability within family transparency. The tension between individual responsibility and collective goals requires design supporting both perspectives enabling each family member to see their contribution while maintaining household-level transparency that prevents surveillance concerns.
- **Principle 3:** Layer complexity to serve diverse literacies simultaneously. Rather than choosing between simplification (alienating sophisticated users) or comprehensiveness (overwhelming novices), effective family interfaces reveal complexity progressively, allowing different users to engage at appropriate depth levels.
- **Principle 4:** Emphasize actionable device-level insights over abstract totals. Granular data revealing specific consumption sources enables targeted behavior changes that aggregate data cannot support. Family members need to know "which devices use most energy" more than "total household consumption."
- **Principle 5:** Integrate multiple engagement pathways for different motivations. Competitive elements engage some family members, analytical capabilities serve others, and visual immediacy attracts yet others successful family systems support multiple simultaneous pathways rather than forcing unified approaches.
- **Principle 6:** Contextualize energy data through relative comparison and meaningful framing. Raw numerical values alone often lack interpretability for household users unfamiliar with energy metrics. Effective interface therefore represent consumption within comparative contexts such as previous usage, household goals, historical trends, or financial costs enabling users to interpret abstract data through meaningful reference points that support decision-making and behavioral understanding.
- **Principle 7:** Support long-term habit formation rather than continuous intensive engagement. Behavioral change may persist even as interaction frequency declines, suggesting systems should help families internalize conservation routines rather than depend on constant attention. Interfaces should therefore transition from intensive early feedback toward lighter maintenance-oriented support as habits stabilize.

7.2. Practical Implications

7.2.1. For smart home technology design

Smart home technology developers should recognize that family adoption fundamentally differs from individual adoption. Products designed for single users fail when deployed in households with heterogeneous needs, varying technical skills, and distributed decision-making.

Design for heterogeneity from the start. Rather than targeting average users, assume user populations span 8-year-olds to 80-year-olds, novices to experts. Progressive disclosure, redundant encoding (visual + textual), and flexible complexity levels should be standard rather than afterthoughts.

Prioritize local data processing and storage. Privacy concerns significantly affect family adoption. Systems processing data locally rather than uploading to external servers address these concerns while providing additional benefits of reliability (continued operation during internet outages) and responsiveness (no cloud round-trip latency).

Reduce setup complexity drastically. The technical barriers encountered in this deployment—Raspberry Pi configuration, network setup, integration complexity—would prevent most family adoption. Commercial systems must achieve plug-and-play simplicity approaching appliance installation rather than requiring IT expertise. Plan for maintenance and support. Families won't maintain systems requiring regular technical intervention. Either systems must be sufficiently robust to operate unattended for months, or manufacturers must provide accessible support infrastructure handling troubleshooting and updates.

For energy policy and education Policymakers and energy educators should recognize that information provision must be well-designed to drive behavior change.

Invest in usable feedback systems, not just smart meters. Deploying smart meters that provide data utilities can access but households cannot easily use misses conservation opportunities. Policy should incentivize or require user-friendly residential interfaces translating meter data into actionable household insights. Target high-discretion consumption in education campaigns. The finding that entertainment and computing devices showed largest reductions (31% and 24%) while kitchen appliances changed minimally (3%) suggests education should focus where behavior change is feasible. Campaigns emphasizing standby power elimination and computer sleep modes will prove more effective than generic save energy messaging.

Leverage family social dynamics in program design. Energy efficiency programs targeting individual household members miss the amplification potential of family discussions and collective goal-setting. Programs could provide family challenges, multi-generational educational materials, and shared incentives that harness social reinforcement.

Recognize that cost motivation dominates environmental concern for most households. While environmental sustainability matters, this research confirms that financial savings drive behavior more powerfully for most families. Effective communication should lead with economic benefits while connecting to environmental impacts secondarily.

7.2.2. For family-centered technology development

Developers creating technologies for family contexts whether energy management, scheduling, communication, or education tools should apply lessons from this research.

Conduct family-inclusive user research. Traditional user research focusing on individual participants misses critical family dynamics, power structures, and collective use patterns. Research should include multiple family members, observe collaborative use, and investigate how technologies mediate family relationships. Design for varying engagement levels across members. Not all family members will engage equally with shared technologies. Design should accommodate primary users (who check frequently, use advanced features), secondary users (who engage occasionally for specific needs), and passive beneficiaries (who don't engage directly but benefit from others' use).

Balance transparency with privacy. Families need appropriate information sharing to coordinate and collaborate, but members also need autonomy and privacy. Rather than maximizing transparency or maximizing privacy, design should enable configurable boundaries reflecting diverse family norms and preferences.

Test in real households over extended periods. Lab studies and short-term deployments miss critical patterns—how novelty fades, how systems integrate into routines, how technical issues affect long-term satisfaction. Extended in-home testing with actual families should be standard for family-oriented technologies.

7.2.3. Recommendations for Family Energy Dashboard Designers

Designers specifically creating energy dashboards for families should implement:

- Real-time overview as entry point. Make current consumption status (numerical + color-coded gauge) the first thing users see, as this immediate feedback drives initial engagement and enables quick checking.

- Device-level granularity, not just totals. Invest in monitoring individual devices rather than only whole-home consumption. The actionable insights enabling specific behavior changes justify the additional cost and complexity.

- Prominent cost translation everywhere. Convert technical units (kWh, Watts) to financial costs throughout the interface, as economic motivation drives most users more than environmental metrics or technical measurements.

- Comparison context for every metric. Never show consumption values without comparison to previous periods, goals, or household averages. Context transforms meaningless numbers into actionable insights.

- Multiple visualization types for different questions. Provide bar charts for device comparison, line graphs for temporal trends, simple gauges for current status different analytical questions need different visual forms.

- Configurable privacy and permissions. Enable parents to control what children see, create member-specific views, and adjust transparency levels to match family norms rather than imposing single access model.

- Minimal notification strategy. Alert only on exceptions (anomalies, threshold violations), not routine status. Users who check regularly find routine notifications annoying; infrequent checkers won't engage with notifications regardless of content.

7.3. Future Research Directions

This research opens numerous promising avenues for future investigation.

Scaling to larger populations

The single-family autoethnographic deployment requires validation across diverse households. Future research should deploy the system with 20-50 families varying in: household structure (nuclear families, single-parent, multi-generational, childless couples), socioeconomic status (low-income households where energy costs are critical burdens versus higher-income where costs are negligible), technical literacy (from tech-enthusiast early adopters to technology-resistant late adopters), and housing types (renters in apartments, homeowners in houses, varying climates and energy sources).

This larger-scale deployment would establish generalizability of findings, identify which design principles transfer broadly versus which require context-specific adaptation [80], and reveal whether the 18% energy reduction observed here represents typical or exceptional outcomes.

Long-term behavior change studies

The six-week deployment captured initial adoption and early behavior change but cannot assess sustainability beyond novelty periods. Critical questions remain: Do consumption reductions persist at 6 months? 12 months? What proportion of users continue engaging after a year? Which features sustain value versus which become ignored?

Longitudinal studies tracking households for 6-12 months would reveal persistence of behavior changes, identify factors predicting long-term engagement versus abandonment, and distinguish habitual internalization (changes that continue without monitoring) from monitoring-dependent behaviors (that revert when checking stops).

Advanced AI integration possibilities

Current dashboard functionality is largely descriptive showing what happened with minimal predictive or prescriptive capabilities. Future iterations could integrate machine learning for the function Predictive consumption.

Predictive consumption modeling forecasting next month's usage based on current patterns, enabling proactive conservation before bills arrive. Anomaly detection algorithms automatically identifying unusual consumption without manual threshold setting. Personalized recommendations suggesting specific conservation actions tailored to individual household patterns rather than generic advice. Adaptive goals that adjust targets based on historical achievability, maintaining motivation without frustration.

However, AI integration must be carefully designed to maintain transparency and user control black-box algorithms that make opaque decisions undermine trust and agency that human-interpretable visualizations support [51].

Comparative Autoethnographic Studies Across Multiple Families

Rather than choosing between autoethnographic depth and traditional breadth, future research could combine both through comparative autoethnography where multiple researcher-families simultaneously deploy systems in their own households [27]. This approach would preserve insider perspective depth while enabling cross-family comparison revealing generalizable versus idiosyncratic patterns.

Three to five researcher families with diverse structures and demographics could provide both rich contextual understanding and sufficient variation to identify robust patterns versus unique circumstances. Collaborative analysis where researchers compare their families' experiences would surface insights single autoethnographies miss [27].

Longitudinal Tracking of Sustained Behavior Change

Beyond monitoring dashboard engagement, future research should track whether specific behavior changes (device power-off routines, load shifting, standby elimination) persist after monitoring ends. Ideal methodology would involve: baseline measurement (pre-monitoring consumption), intervention period (active dashboard use with measurements), monitoring withdrawal (dashboard removed but consumption still measured), and follow-up (6 months post-withdrawal checking for sustained changes).

This design would distinguish internalized habits (behaviors that continue independently) from monitoring-dependent actions (requiring ongoing feedback to sustain), revealing which conservation strategies become permanent versus which need continuous reinforcement.

Additional Promising Directions

Cross-cultural studies examining whether findings transfer across different cultural contexts with varying attitudes toward privacy, family structure, and environmental responsibility. Integration with home automation where insights from dashboards automatically trigger actions (turning off forgotten devices, scheduling loads for off-peak times) rather than requiring manual response [71]. Peer comparison networks enabling neighborhood-level social comparison and collective challenges while managing privacy concerns. Educational curriculum integration where children's classroom learning about energy connects to home monitoring, bridging school and domestic contexts.

7.4. Final Remarks

This research demonstrates that the challenge of residential energy conservation is fundamentally a human-computer interaction challenge, not merely a technical or economic problem. The technology enabling device-level energy monitoring already exists and is increasingly affordable. The barrier preventing widespread household adoption and meaningful behavior change lies in interface design that fails to serve diverse family members, provide actionable insights rather than overwhelming data, and sustain engagement beyond initial novelty.

The autoethnographic approach, while limited in generalizability, revealed insights about how energy monitoring technology integrates into actual family life the spontaneous conversations it catalyzes, the routines it shapes, the learning it enables across generations—that would remain invisible in traditional research methods [47]. These insights inform design principles applicable beyond this specific family: progressive complexity disclosure, collaborative viewing optimization, actionable granularity, and multiple engagement pathways serving heterogeneous users.

The measured 18% energy reduction, corroborated by convergent self-reported behavior changes across all family members, proves that well-designed information systems can indeed drive meaningful action. The specificity of changes standby elimination, sleep mode adoption, load shifting demonstrates that visibility enables accountability, which enables targeted action addressing identified high-consumption sources.

Looking forward, the path to widespread residential energy conservation requires moving beyond viewing households as passive consumption units toward recognizing them as complex social systems capable of collective action when empowered with appropriate tools. Technology designers must shift from optimizing for individual users toward designing for family ecosystems with distributed agency and heterogeneous needs. Policymakers must recognize that deploying monitoring infrastructure without investing in usable interfaces wastes conservation potential. Researchers must embrace methodological diversity, combining autoethnographic depth with quantitative breadth, experimental rigor with interpretive richness.

Ultimately, sustainable residential energy use depends not on technology alone, nor on individual willpower alone, but on the thoughtful integration of technology with human needs, capabilities, and social contexts. This thesis contributes one detailed example of what such integration can achieve when HCI principles guide design, when families are treated as active participants rather than passive subjects, and when research methods match the intimate, complex, long-term nature of domestic technology adoption. The insights generated here both the successes to replicate and the limitations to overcome provide foundation for the next generation of family-centered sustainable technology that empowers households to take meaningful action toward environmental stewardship [51].

Declaration on the Use of AI

During the preparation of this Master's thesis, I used Large Language Models (LLMs) to improve the language of the text. Their use was limited to grammar checking, proofreading, and translation support to make the thesis clearer and easier to read. All research design, data analysis, and software development for the WattExplorer system were completed by me. The thematic analysis was carried out following the method of Braun and Clarke, and all results from the pre-deployment and field study interviews are my own original interpretations.

Bibliography

[1] The methodology of participatory design. *Technical Communication*, 52(2), 2005.

[2] *Publication manual of the American psychological association*. American psychological association, Washington (D.C.), 6th edition edition, 2010.

[3] Wokje Abrahamse and Linda Steg. How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *Journal of economic psychology*, 30(5):711–720, 2009.

[4] Wokje Abrahamse, Linda Steg, Charles Vlek, and Talib Rothengatter. A review of intervention studies aimed at household energy conservation. *Journal of environmental psychology*, 25(3):273–291, 2005.

[5] Icek Ajzen. The theory of planned behavior. *Organizational behavior and human decision processes*, 50(2):179–211, 1991.

[6] Hunt Allcott. Social norms and energy conservation. *Journal of public Economics*, 95(9-10):1082–1095, 2011.

[7] Ernesto Arroyo, Leonardo Bonanni, and Ted Selker. Waterbot: exploring feedback and persuasive techniques at the sink. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 631–639, 2005.

[8] Home Assistant. Home assistant documentation, Feb 2026.

[9] Luigi Atzori, Antonio Iera, and Giacomo Morabito. The internet of things: A survey. *Computer networks*, 54(15):2787–2805, 2010.

[10] Nazmiye Balta-Ozkan, Rosemary Davidson, Martha Bicket, and Lorraine Whitmarsh. Social barriers to the adoption of smart homes. *Energy Policy*, 63:363–374, 2013.

[11] Andrew Banks and Rahul Gupta. Mqtt version 3.1. 1. *OASIS standard*, 29:89, 2014.

[12] Scott Bateman, Regan L Mandryk, Carl Gutwin, Aaron Genest, David McDine, and Christopher Brooks. Useful junk? the effects of visual embellishment on comprehension and memorability of charts. In *Proceedings of the SIGCHI conference on human factors in computing systems*, pages 2573–2582, 2010.

[13] Virginia Braun and Victoria Clarke. Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2):77–101, 2006.

[14] John Brooke et al. Sus-a quick and dirty usability scale. *Usability evaluation in industry*, 189(194):4–7, 1996.

[15] John N. A. Brown. *Building an Intuitive Multimodal Interface for a Smart Home: Hunting the SNARK*. Human-Computer Interaction Ser. Springer, Cham, 2017.

[16] Alan Bryman. *Social research methods*. Oxford University Press, Oxford, fifth edition edition, 2016.

[17] Hung-Ming Chen, Chun-Wei Lin, Shang-Hsien Hsieh, Hsuan-Fu Chao, Chuin-Shan Chen, Ruei-Shiue Shiu, Shiang-Ru Ye, and Yu-Chang Deng. Persuasive feedback model for inducing energy conservation behaviors of building users based on interaction with a virtual object. *Energy and Buildings*, 45:106–115, February 2012.

[18] John W Creswell and Vicki L Plano Clark. *Designing and conducting mixed methods research*. Sage publications, 2017.

[19] Sara J Czaja and Chin Chin Lee. The impact of aging on access to technology. *Universal access in the information society*, 5(4):341–349, 2007.

[20] Sarah Darby et al. The effectiveness of feedback on energy consumption. *A Review for DEFRA of the Literature on Metering, Billing and direct Displays*, 486(2006):26, 2006.

[21] Fred D Davis et al. Technology acceptance model: Tam. *Al-Suqri, MN, Al-Aufi, AS: Information seeking behavior and technology adoption*, 205(219):5, 1989.

[22] Norman K. Denzin. *The Research Act: A Theoretical Introduction to Sociological Methods*. Routledge, 1 edition, july 2017.

[23] Jan E. DeWaters and Susan E. Powers. Energy literacy of secondary students in new york state (usa): A measure of knowledge, affect, and behavior. *Energy Policy*, 39(3):1699–1710, March 2011.

[24] John Dewey. *Logic-The theory of inquiry*. Read Books Ltd, 2018.

[25] Thomas Dietz, Gerald T Gardner, Jonathan Gilligan, Paul C Stern, and Michael P Vandenbergh. Household actions can provide a behavioral wedge to rapidly reduce us carbon emissions. *Proceedings of the national academy of sciences*, 106(44):18452–18456, 2009.

[26] Karen Ehrhardt-Martinez, Kat A Donnelly, Skip Laitner, et al. Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities. American Council for an Energy-Efficient Economy Washington, DC, 2010.

[27] Carolyn Ellis. Revisioning an ethnographic life: Integrating a communicative heart with a sociological eye. 2012.

[28] Carolyn Ellis, Tony E Adams, and Arthur P Bochner. Autoethnography: an overview. *Historical social research/Historische sozialforschung*, pages 273–290, 2011.

[29] Gary W Evans, Gernot Brauchle, Aliya Haq, Rachel Stecker, Kimberly Wong, and Elan Shapiro. Young children's environmental attitudes and behaviors. *Environment and behavior*, 39(5):635–658, 2007.

[30] Xi Fang, Satyajayant Misra, Guoliang Xue, and Dejun Yang. Smart grid—the new and improved power grid: A survey. *IEEE communications surveys & tutorials*, 14(4):944–980, 2011.

[31] Ahmad Faruqui and Sanem Sergici. Household response to dynamic pricing of electricity: a survey of 15 experiments. *Journal of regulatory Economics*, 38(2):193–225, 2010.

[32] Linda Finlay. Negotiating the swamp: the opportunity and challenge of reflexivity in research practice. *Qualitative research*, 2(2):209–230, 2002.

[33] Corinna Fischer. Feedback on household electricity consumption: a tool for saving energy? *Energy efficiency*, 1(1):79–104, 2008.

[34] Arthur D. Fisk, Sara J. Czaja, Wendy A. Rogers, Neil Charness, Sara J. Czaja, and Joseph Sharit. *Designing for Older Adults: Principles and Creative Human Factors Approaches, Second Edition.* CRC Press, 0 edition, November 2018.

[35] Elisha R Frederiks, Karen Stenner, and Elizabeth V Hobman. Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. *Renewable and sustainable energy reviews*, 41:1385–1394, 2015.

[36] Pierre Friedlingstein, Matthew W Jones, Michael O'Sullivan, Robbie M Andrew, Dorothee CE Bakker, Judith Hauck, Corinne Le Quéré, Glen P Peters, Wouter Peters, Julia Pongratz, et al. Global carbon budget 2021. *Earth system science data*, 14(4):1917–2005, 2022.

[37] Jon Froehlich, Leah Findlater, and James Landay. The design of eco-feedback technology. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, page 1999–2008, Atlanta Georgia USA, April 2010. ACM.

[38] José-Alberto García-Avilés. Diffusion of innovation. *The international Encyclopedia of media psychology*, 1(8):1–8, 2020.

[39] Kirsten Gram-Hanssen. Residential heat comfort practices: understanding users. *Building Research & Information*, 38(2):175–186, 2010.

[40] Shelly Group. Shelly plug s technical specifications, Feb 2026.

[41] Jan Gulliksen, Bengt Göransson, Inger Boivie, Stefan Blomkvist, Jenny Persson, and Åsa Cajander. Key principles for user-centred systems design. *Behaviour & Information Technology*, 22(6):397–409, November 2003.

[42] Juho Hamari, Jonna Koivisto, and Harri Sarsa. Does gamification work? – a literature review of empirical studies on gamification. In *2014 47th Hawaii International Conference on System Sciences*, pages 3025–3034, 2014.

[43] Tom Hargreaves. Beyond energy feedback. *Building Research & Information*, 46(3):332–342, 2018.

[44] George W Hart. Nonintrusive appliance load monitoring. *Proceedings of the IEEE*, 80(12):1870–1891, 1992.

[45] IEA and AIE. *Global EV Outlook 2023: Catching up with Climate Ambitions*. OECD Publishing: Editions OCDE, Paris, 2023.

[46] Kathryn B Janda. Buildings don't use energy: people do. *Architectural science review*, 54(1):15–22, 2011.

[47] Sami Karjalainen. Consumer preferences for feedback on household electricity consumption. *Energy and Buildings*, 43(2–3):458–467, February 2011.

[48] Dongsu Kim, Yeobeom Yoon, Jongman Lee, Pedro J. Mago, Kwangho Lee, and Heejin Cho. Design and implementation of smart buildings: A review of current research trend. *Energies*, 15(12), 2022.

[49] Henrik Lund, Poul Alberg Østergaard, David Connolly, and Brian Vad Mathiesen. Smart energy and smart energy systems. *Energy*, 137:556–565, 2017.

[50] Osama A. Marzouk. Summary of the 2023 (1st edition) report of tcep (tracking clean energy progress) by the international energy agency (iea), and proposed process for computing a single aggregate rating. *E3S Web Conf.*, 601:00048, 2025.

[51] Brent Mittelstadt, Chris Russell, and Sandra Wachter. Explaining explanations in ai. In *Proceedings of the Conference on Fairness, Accountability, and Transparency*, FAT* '19, page 279–288, New York, NY, USA, 2019. Association for Computing Machinery.

[52] Stephanie Moser and Silke Kleinhückelkotten. Good intents, but low impacts. *Diverging Importance*, 2018.

[53] Carman Neustaedter and Phoebe Sengers. Autobiographical design in hci research: designing and learning through use-it-yourself. In *Proceedings of the designing interactive systems conference*, pages 514–523, 2012.

[54] Richard G Newell and Juha Siikamäki. Nudging energy efficiency behavior: The role of information labels. *Journal of the Association of Environmental and Resource Economists*, 1(4):555–598, 2014.

[55] Jakob Nielsen. How to conduct a heuristic evaluation. *Nielsen Norman Group*, 1(1):8, 1995.

[56] Donald A Norman and Stephen W Draper. *User centered system design; new perspectives on human-computer interaction.* L. Erlbaum Associates Inc., 1986.

[57] A Norman Donald. *The design of everyday things.* MIT Press, 2013.

[58] William T Odom, Abigail J Sellen, Richard Banks, David S Kirk, Tim Regan, Mark Selby, Jodi L Forlizzi, and John Zimmerman. Designing for slowness, anticipation and re-visitation: a long term field study of the photobox. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1961–1970, 2014.

[59] Brian Orland, Nilam Ram, Dean Lang, Kevin Houser, Nate Kling, and Michael Coccia. Saving energy in an office environment: A serious game intervention. *Energy and Buildings*, 74:43–52, May 2014.

[60] John E Petersen, Vladislav Shunturov, Kathryn Janda, Gavin Platt, and Kate Weinberger. Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. *International Journal of Sustainability in Higher Education*, 8(1):16–33, 2007.

[61] Raspberry Pi. Raspberry pi documentation, Feb 2026.

[62] J. Piaget. Intellectual evolution from adolescence to adulthood. *Human Development*, 15(1):1–12, 1972.

[63] James Pierce, Diane J. Schiano, and Eric Paulos. Home, habits, and energy: examining domestic interactions and energy consumption. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, page 1985–1994, New York, NY, USA, 2010. Association for Computing Machinery.

[64] Jean Paul Sebastian Piest, Yoshimasa Masuda, Osamu Nakamura, and Koray Karaca. Human-centred design thinking using the intelligence amplification design canvas and the adaptive integrated digital architecture framework. In *International KES Conference on Human Centred Intelligent Systems*, pages 153–163. Springer, 2023.

[65] Data Protection. General data protection regulation. *Intersoft Consulting, Accessed in October*, 24(1), 2018.

[66] Yvonne Rogers, Jenny Preece, and Helen Sharp. *Interaction design: beyond human-computer interaction.* Wiley, Chichester, 3. ed., repr edition, 2012.

[67] Elizabeth B.-N. Sanders and Pieter Jan Stappers. Co-creation and the new landscapes of design. *CoDesign*, 4(1):5–18, mar 2008.

[68] P Wesley Schultz, Jessica M Nolan, Robert B Cialdini, Noah J Goldstein, and Vladas Griskevicius. The constructive, destructive, and reconstructive power of social norms. *Psychological science*, 18(5):429–434, 2007.

[69] Weisong Shi, Jie Cao, Quan Zhang, Youhuizi Li, and Lanyu Xu. Edge computing: Vision and challenges. *IEEE internet of things journal*, 3(5):637–646, 2016.

[70] Ben Shneiderman. Universal usability. *Commun. ACM*, 43(5):84–91, May 2000.

[71] Elizabeth Shove. Beyond the abc: climate change policy and theories of social change. *Environment and planning A*, 42(6):1273–1285, 2010.

[72] Herbert Alexander Simon and K Anders Ericsson. Protocol analysis: Verbal reports as data. *(No Title)*, 1984.

[73] Ewan Soubutts. *Aging in place together: journeys towards adoption and acceptance of smart home healthcare technology.* PhD thesis, University of Bristol, 2023.

[74] Linda Steg. Promoting household energy conservation. *Energy policy*, 36(12):4449–4453, 2008.

[75] Yolande Strengers. Smart energy in everyday life: are you designing for resource man? *interactions*, 21(4):24–31, 2014.

[76] John Sweller. Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12(2):257–285, April 1988.

[77] Abbas Tashakkori, Budi Puspa Priadi, and Charles Teddlie. *Mixed methodology: mengombinasikan pendekatan kualitatif dan kuantitatif.* Pustaka Pelajar, Yogyakarta, 2010.

[78] Edward R. Tufte. *The visual display of quantitative information.* Graphics Press, Cheshire, Conn, 2nd ed., 8th print edition, 2013.

[79] Charlie Wilson and Hadi Dowlatabadi. Models of decision making and residential energy use. *Annual Review of Environment and Resources*, 32(1):169–203, November 2007.

[80] Robert K Yin. *Qualitative research from start to finish.* Guilford publications, 2015.

[81] Eric Zeng, Shrirang Mare, and Franziska Roesner. End user security and privacy concerns with smart homes. In *thirteenth symposium on usable privacy and security (SOUPS 2017)*, pages 65–80, 2017.

[82] Ahmed Zoha, Alexander Gluhak, Muhammad Ali Imran, and Sutharshan Rajasegarar. Non-intrusive load monitoring approaches for disaggregated energy sensing: A survey. *Sensors*, 12(12):16838–16866, 2012.

[83] Diana Ürge Vorsatz, Luisa F. Cabeza, Susana Serrano, Camila Barreneche, and Ksenia Petrichenko. Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews*, 41:85–98, 2015.

A. Appendix

A.1. Informed Consent Form

A.1.1. Consent Form for adults (Pre-Deployment Interviews)

INFORMED CONSENT TO PARTICIPATE IN RESEARCH

PROJECT TITLE: DESIGN AND EVALUATION OF A WEB APPLICATION TO FOSTER ENERGY SAVING IN FAMILIES

Principal Investigator: Srujana Konduri
University of Vienna

INVITATION TO PARTICIPATE

You are invited to participate in a research study about household energy use and monitoring technology. This study is being conducted as part of a Master's thesis in Human-Computer Interaction.

PURPOSE

The purpose of this study is to understand how families think about energy consumption and what features would be useful in an energy monitoring dashboard.

PROCEDURES

If you agree to participate, you will:

- Participate in a 30–45-minute audio-recorded interview about your household energy use and technology preferences
- Answer questions about your family's energy behaviors and attitudes
- Optionally, participate in future phases (prototype testing, system deployment) if invited

RISKS AND BENEFITS

Risks are minimal. You may feel slight discomfort discussing household habits or energy costs. There are no direct benefits to you, though your participation will contribute to research on sustainable technology.

CONFIDENTIALITY

Your responses will be kept confidential. Audio recordings will be transcribed and stored securely. Your name will be replaced with a pseudonym in all research outputs. Only the research team will have access to identifiable data.

VOLUNTARY PARTICIPATION

Your participation is completely voluntary. You may refuse to answer any question or withdraw at any time without penalty.

CONTACT INFORMATION

Questions about the study: ko*********4@gmail.com

CONSENT

I have read and understand the above information. I agree to participate in this research study.

Signature: __________________________ Date: __________

Name: __________________________

A.1.2. Child Assent Form (Ages 8-17)

RESEARCH STUDY ASSENT FORM FOR CHILDREN
(A parent or guardian must also give permission)

Study Title: Family Energy Dashboard Study

What is this study about?

I'm studying how families learn about the energy they use at home. I want to understand what would help families save energy.

What will I do?

I'll ask you questions about energy use in your home. Like:

- Do you think about electricity?
- What devices do you use?
- Would you want to see how much energy things use?

The interview will take about 15-30 minutes. I'll record our conversation so I can remember what you said.

Do I have to participate?

No! It's completely your choice. Even if your parents said yes, you can say no. You can also stop at any time or skip questions you don't want to answer.

Will anyone know what I said?

No. I'll use a fake name instead of your real name when I write about the study. Your teachers and friends won't know what you said.

Questions?

You can ask me anything about the study anytime.

Do you want to participate in this study?

□ YES, I want to participate
□ NO, I don't want to participate

Child's Name: ___________________________

Child's Signature: _______________________ Date: ___________

Parent / Guardian Signature: _________________

A.1.3. Consent Form for Field Study

FIELD STUDY CONSENT FORM (ADULT PARTICIPANTS)

DATA COLLECTION

The study may collect:

- Dashboard interaction and usage data
- Household energy consumption information
- Feedback shared during interviews or discussions

No sensitive personal information unrelated to the study will be collected.

RISKS AND BENEFITS

Risks are minimal. Some participants may experience slight discomfort discussing household routines or energy consumption habits.

There are no direct personal benefits, but your participation will contribute to research on sustainable technology and family-centered energy awareness systems.

CONFIDENTIALITY

All collected data will be treated confidentially and stored securely. Your identity will be replaced with a pseudonym in all reports, publications, and presentations. Only the research team will have access to identifiable information.

VOLUNTARY PARTICIPATION

Your participation is completely voluntary. You may withdraw from the study at any time without penalty and request that your data no longer be used.

CONSENT

By participating in this field study, you confirm that:

You have read and understood the information above;

You voluntarily agree to participate in the study ;

You understand that you may withdraw at any time

A.2. Interview Protocols

A.2.1. Pre-deployment interview protocol

Duration: 30-45 minutes (adults), 20-30 minutes (teenagers), 15-20 minutes (children)
Setting: Participant's home when possible, comfortable public location as alternative
Recording: Audio recorded with consent

Introduction and Warm-Up

"*Thank you for participating in this study about household energy use and technology. This conversation will take about 30 minutes. I'll ask you questions about how you think about energy in your home and what might help you understand your energy use better. There are no right or wrong answers I'm interested in your honest experiences and opinions.*"

A.2.2. Questionnaire

Specific Questions for Environmental Advocates

1. How important is it for you to monitor and reduce your energy consumption?
2. What features would help you track your progress in reducing energy usage?
3. How can the dashboard provide information on the environmental impact of your energy consumption?
4. Do you think the dashboard should include tips or challenges for reducing energy usage?
5. How often would you like to receive updates on your energy usage and its environmental impact?

Specific Questions for Homemakers

1. How do you currently manage your household's energy consumption?
2. What challenges do you face in understanding or reducing your energy usage?
3. What features would make the dashboard more useful for managing your household's energy?
4. How can the dashboard help you involve other family members in saving energy?
5. Do you think the dashboard should include reminders or alerts for high energy usage? If so, how often?
6. What kind of information would help you make better decisions about energy usage in your home?

Specific Questions for Kids (under 12)

1. Do you know what it means when we talk about "energy consumption"?
2. What kind of information would you like to see about the energy used by your toys or devices?
3. Would you like to see fun facts or tips about how to save energy?
4. How can we make the dashboard more interesting and fun for kids like you?
5. Do you think saving energy is important? Why?
6. What colors or designs would you like to see on the dashboard?

Specific Questions for Students (12-24)

1. How important is it for you to keep track of your energy consumption?
2. What types of graphs or charts do you find most helpful for understanding data?
3. Would you like to set personal goals for reducing your energy usage?
4. How can the dashboard help you learn more about saving energy and its benefits?
5. Do you think your friends or classmates would be interested in using this dashboard? Why or why not?
6. What kind of notifications or alerts would be most useful for you?

Specific Questions for Working People (25-60)

1. 1. How does keeping track of your energy consumption fit into your daily routine?
2. 2. What specific information about your energy usage is most important to you (e.g., cost, usage by device)?
3. 3. How can the dashboard help you save time and money on your energy bills?
4. 4. Would you find it useful to compare your energy usage with similar households?
5. 5. Do you think the dashboard should offer tips or suggestions for reducing energy consumption? If so, what kind?
6. 6. How often would you like to receive updates or reports on your energy usage?
7. "Thank you so much for your time and insights. Your responses will help design a system that actually meets families' needs."

Specific Questions for Seniors (60+)

1. How do you currently monitor your energy consumption?
2. What difficulties do you face in understanding your energy usage?
3. What features would make the dashboard easier for you to use?
4. How can the dashboard help you save on your energy bills?
5. Do you prefer larger text or simpler graphics on the dashboard?
6. How often would you like to receive updates about your energy usage?

Specific Questions for Tech Enthusiasts

1. How do you currently track your energy consumption?
2. What advanced features would you like to see in the dashboard (e.g., integration with other smart devices)?
3. How can the dashboard provide more detailed analytics on energy usage?
4. Do you think the dashboard should offer customization options? If so, what kind?
5. How often would you like to receive detailed reports on your energy usage?

General Questions (for all groups)

1. How often do you check how much energy your household is using?
2. Which devices or appliances in your home do you think use the most energy?
3. When you look at your current energy usage data, do you find it easy to understand?
4. What features or information would you like to see in an energy consumption dashboard?
5. How would you prefer to receive updates about your energy usage (e.g., email, app notifications, SMS)?
6. Do you think its important to monitor energy consumption? Why or why not?
7. Have you ever tried to reduce your energy usage? If so, how?

A.3. Post-deployment interview protocols

All post-deployment interviews follow semi-structured format with core questions and flexible follow-up probes. Interviews are audio recorded and transcribed.

A.3.1. Father interview questions

Part A: Initial Reactions and Expectations

1. When Srujana first told you about this energy dashboard project, what was your immediate reaction? Were you excited, skeptical, indifferent? Why?

2. What did you expect the dashboard would do for our family? Has that expectation changed now? What surprised you? What met your expectations?

3. How did you feel about having energy monitoring in our home? Any privacy or surveillance concerns? Did you worry about being "watched" or judged for your usage?

Part B: Usage Patterns and Engagement

4. How often did you check the dashboard over these 7 weeks? What made you check it? Daily? Weekly? Only when reminded? What triggered your checking?

5. Can you walk me through a typical session when you opened the dashboard? What did you look at first? Which features did you use most? Which did you ignore?

6. Were there specific times of day or situations when you were more likely to check the dashboard? Morning? Evening? After getting bills? When devices were on?

7. Did you ever use the dashboard on your phone versus computer? Which did you prefer and why?

8. What made you want to check the dashboard? What made you forget about it?

Part C: Behavioral Changes and Impact

9. Tell me about any changes you made in how you use energy since we started using the dashboard. Give me specific examples. Turning things off? Timing changes? New habits? Why those specific changes?

10. Has the dashboard changed how you think about energy consumption? How? More conscious? More knowledgeable? Changed priorities?

11. Can you estimate how much energy or money you think we've saved, if any?

12. Were there things you learned about our energy use that genuinely surprised you?

Part D: System Usability and Features

13. What frustrated you about using the dashboard? What was difficult or confusing? Technical issues? Interface confusion? Missing features?

14. What did you find most useful about the system?

15. If you could change or add anything to the dashboard, what would it be? What features would make you use it more? What's missing?

16. How would you rate the dashboard's ease of use on a scale of 1-10? What would make it a 10?

Part E: Notifications and Communication (3-4 minutes)

17. How did you feel about the notification system? Too much? Too little? Useful? Did you act on notifications? Ignore them? What would improve them?

18. Did the dashboard change how our family talks about energy? Give me examples.

Part F: Overall Satisfaction and Future Use (3-4 minutes)

19. On a scale of 1-10, how satisfied are you with the system overall?

20. Would you want to continue using it after this study ends? Why or why not?

21. Would you recommend this system to other families? What would you tell them?

22. Any other thoughts or feedback about the experience?

A.3.2. Mother (researcher-participant) interview questions

Part A: Dual Role Reflection

1. How did your role as both the developer and a family member using the system affect your experience? Did you feel pressure to make it work? Hard to be objective? Special insights?

2. Were there moments when you felt conflicted between being the researcher and being a family member? Describe them. Times when family needs conflicted with research goals?

3. Did you ever catch yourself using the dashboard as researcher (checking for bugs, monitoring data collection) versus as family member (genuinely curious about consumption)?

4. How do you think your family members felt about you being both designer and fellow user?

   Part B: Design Validation

5. Looking back at your initial design ideas, what worked better than expected? What didn't work as planned? Surprises in actual use vs. design intentions?

6. Which features that you were excited about turned out to be less important? Which ones that seemed minor became critical?

7. How did your understanding of our family's needs evolve during the deployment? What did you learn about family members that surprised you?

8. If you were designing this for another family from scratch, what would you do differently?

Part C: Personal Usage and Behavior

9. How often did you check the dashboard, and was that as researcher monitoring the system or as family member checking our usage? Can you separate the two roles? Which drove your checking more?

10. Did you change your own energy behaviors? If so, what motivated those changes? Because of data insights? To set example? To validate system?

11. What features did you find yourself using most as a family member (not as researcher)?

12. Were there times you were frustrated with your own design choices?

Part D: Family Dynamics Observations

13. How did different family members engage with the dashboard differently than you expected? Surprises in who used it more/less? How they used it?

14. Describe a moment when you saw the dashboard genuinely impact our family's behavior or discussions.

15. Did being the designer change how you interacted with family members about energy? Did you push them to use it? Hold back from suggesting features?

16. How did the system affect family dynamics? Positive? Negative? Examples?

Part E: Technical Challenges

17. What technical challenges did you face that you didn't anticipate? How did they affect the family's experience? System failures, data inaccuracies, connectivity issues?

18. When technical problems occurred, how did you balance fixing them as researcher versus dealing with them as frustrated user?

19. What was harder than expected? What was easier?

Part F: Methodological Reflection

20. What insights did you gain from living with your own research that you couldn't have gotten from studying other families?

21. What were the biggest disadvantages or challenges of studying your own family?

22. Did you ever worry about bias in your observations or interpretations? How did you try to manage that?

23. Would you recommend this autoethnographic approach to other HCI researchers? Under what conditions?

24. How has this experience studying your own family changed how you think about HCI research or family technology design?

Part G: Future Intentions

25. Will you keep the system running after the study formally ends?

26. What changes would you make to the system now, knowing what you know?

A.3.3. Children interview questions

Part A: First Impressions

1. When Mom first showed you the dashboard, what did you think? Was it cool, boring, confusing?

2. Did you understand what the dashboard was for? What did you think it would do?

3. How did you feel about having something that shows how much electricity your devices use?

Part B: Using the Dashboard

4. How often did you look at the dashboard? Every day? Once a week? Only when Mom asked you to?

5. Show me: What did you look at when you opened the dashboard? What was your favorite part?

6. Was it easy to use or hard? What was confusing?

7. Did you ever check the dashboard on your own, without anyone asking you to? Why or why not?

8. What would make you check it more on your own?

Part C: Learning and Understanding

9. Did you learn anything about energy or electricity from using the dashboard? What?

10. Were you surprised by anything you saw on the dashboard?

11. Can you tell me which of your devices uses the most electricity?

12. Did you talk about what you learned with friends or at school?

Part D: Behavior Changes

13. Did you change anything you do because of the dashboard? Like turning things off more?

14. Did the dashboard make you want to save energy? Why or why not?

15. Is there anything you do differently now compared to before we had the dashboard?

16. Do you think you'll keep doing those things even after the study ends?

Part E: Family and Fun

17. Did your family talk about energy more after we started using the dashboard? What kinds of conversations?

18. Was using the dashboard fun, boring, or something else? What would make it more fun?

19. Did you ever look at the dashboard with other family members together? Was that different from looking alone?

Part F: Likes, Dislikes, Improvements

20. What was your favorite thing about the dashboard?
21. What did you not like about it?
22. If you could change one thing about the dashboard, what would it be?
23. Would you want to keep using it? Why or why not?