Volker: An AI-Powered App for Personalized Energy Efficiency Recommendations in Residential Buildings

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In response to rising energy costs and the increasing impact of climate change, we developed a user-centered app prototype, "Volker", with input from end users, tradespeople, drone pilots, and energy consultants. The prototype uses AI-powered analysis of thermographic images to generate personalized energy efficiency recommendations for building occupants. Leveraging Explainable AI, our prototype provides non-experts with accessible, clear, and personalized guidance on energy-saving measures. Our research investigates the usefulness, interpretability, and trustworthiness of thermographic analyses and the recommendations derived from them. The app utilizes thermographic images from both drone and handheld cameras to create detailed housing models, enabling actionable and user-specific recommendations. This paper explores the requirements, design process, and evaluation of the app's user interface and user experience, emphasizing positive and persuasive computing principles to encourage sustainable behaviors. "Volker" not only provides actionable guidance and motivational support to users but also helps maintain their engagement with energy-saving practices. The findings offer insights into the design of user-friendly energy efficiency apps, highlighting the need to adapt solutions to users' real-world conditions and needs to make meaningful contributions to climate action.

CCS Concepts: • **Hardware → Temperature monitoring**; • **Human-centered computing** → *User centered design*; Mobile computing; • **Social and professional topics → Sustainability**.

Additional Key Words and Phrases: Thermography, Building Energy efficiency, drones, Explainable AI (XAI), User Experience (UX), Persuasive Computing, Sustainable Behavior, Positive Computing, Climate Change

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1 INTRODUCTION

In a world increasingly confronted with the effects of climate change, rising energy costs, and the challenges of sustainable energy use, improving energy efficiency in residential buildings has become an urgent priority. Governments in many countries are addressing the need for energy-efficient construction and refurbishment by offering financial

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incentives for such measures [20, 26]. However, these efforts often overlook homeowners' financial constraints, neglect tenants' needs, and fail to consider specific characteristics of buildings, such as location, building materials, year of construction, and condition.

There is a need for innovative, customized approaches to support citizens in their efforts to improve energy efficiency. Modern information technologies and artificial intelligence (AI) can play a critical role in addressing this challenge. Previous research, including work by Benavente-Peces [5], Gabitov et al. [11], and Perea-Moreno et al. [23], emphasizes the potential of technology to enhance energy efficiency in buildings, particularly through the use of sensors and intelligent algorithms.

Our research project "Volker" aims to develop practical, citizen-centric solutions for managing energy consumption in residential buildings. The prototype utilizes thermographic imaging and Explainable AI (XAI) to deliver accessible, user-friendly recommendations for improving energy efficiency. Thermographic technologies, as discussed by Boomsma et al. [6] and Pavlović and Barbaric [22], are crucial as they reveal insights into heat losses and insulation deficiencies. Our approach seeks to make these technologies accessible to a broad audience, eliminating the need for prior technical expertise, and providing a uniquely tailored solution that addresses the financial and informational challenges faced by homeowners and tenants alike.

The core challenge is to create a user-centered tool that not only presents detailed thermographic data but also translates it into an understandable format for non-experts. Studies such as those by Martin et al. [17] and Amaxilatis et al. [3] emphasize the importance of behavior change technologies in mobile and IoT platforms, which have informed our design. To encourage sustainable behaviors, we integrated persuasive technologies and positive computing principles, drawing on Alsalemi et al.'s approach [2], which utilizes "micro-moments" to understand user behavior and deliver targeted recommendations.

A participatory development approach was fundamental to our project, involving input from homeowners, tenants, tradespeople across various sectors, energy consultants, and drone pilots. This participatory method began with extensive user research, allowing target groups to express their needs, challenges, and expectations. Their feedback was incorporated into the development of our prototype, which was subsequently tested and evaluated by participants.

Our research is guided by the following questions:

- **RQ1:** How can AI and thermographic technologies be effectively integrated into a user-friendly application for non-experts?
- **RQ2:** How can participatory development methodologies enhance the relevance and usability of energy efficiency applications?

This paper is structured as follows: first, we present a literature review on energy efficiency and behavior change; next, we discuss the evaluation of the user research; followed by a description of the technical implementation of the app prototype and its functionalities. Finally, we detail the results of the evaluation phase and discuss implications and future developments.

2 RELATED WORK

Our project combines central research areas for increasing energy efficiency in residential buildings with a special focus on the integration of intelligent technologies and human-technology interaction.

2.1 Technological Innovations and Energy Efficiency in Buildings

Research in the field of energy efficiency in buildings focuses on the use of innovative technologies and methods. The work of Benavente-Peces [5], Gabitov et al. [11], and Hoy [15] emphasize the advantages of sensors and intelligent algorithms for energy optimization. Zhu et al. [28] and Pan et al. [21] highlight the influence of technological progress on energy efficiency in the construction industry. In the context of thermography, Boomsma et al. [6] and Pavlović and Barbaric [22] show the effectiveness of this technique in determining heat losses. The studies by Thusyanthan et al. [27] and Han and Huh [13] illustrate how drones and thermal imaging can be used to assess energy efficiency, a topic that is also being investigated in our research project but plays only a minor role in this article. Additionally, Mauriello et al. [18] explore novice approaches to smartphone-based thermographic energy auditing, demonstrating the potential for user-friendly energy efficiency assessments.

2.2 Behavior Change and Psychological Factors

The integration of behavioral change aspects and psychological theories in the development of energy efficiency solutions is crucial to achieve readiness for action among the target group. Studies on behavior change technologies [1, 10] provide valuable insights into user motivation that can be applied to our topic. Studies such as Martin et al. [17] and Amaxilatis et al. [3] show how behavior change technologies can be implemented in apps and IoT-based solutions in the context of sustainability. The work of Boncu, Candel, and Popa [29] shows the success of gamified approaches to promote pro-environmental behavior. Theories such as self-efficacy theory [4] and self-determination theory [24] are essential in this context, as they help explain how users' confidence and intrinsic motivation can be enhanced to support sustainable behavior changes. Bång et al. [8] discuss the role of persuasive visualization in communicating energy consumption data, while Soares et al. [25] provide a comprehensive review of energy efficiency and behavior change research.

2.3 Explainable AI and User-Centricity

The integration of XAI in energy efficiency applications addresses the need for transparency and traceability of AI decisions [16], which is essential to increase user trust but must be tailored to the specific target group. Research in the field of AI for non-experts, represented by the work of McAreavey et al. [19] and Dey et al. [9], emphasizes the importance of user-friendly and transparent AI systems. This underlines the need to make the functioning and decision-making basis of AI-based systems understandable for end users. Alsalemi et al. [2] present an innovative approach that uses micro-moments to understand user behavior and provide effective energy efficiency recommendations for home use. Gilpin et al. [12] offer an overview of interpretability in machine learning, emphasizing the importance of explainability in user-centric AI applications.

2.4 Summary and Importance for "Volker"

To the best of our knowledge, there are no studies in the current research landscape that deal with the combination of technologies and approaches that our project addresses, which include the integration of thermographic imaging, user-friendly interfaces, XAI for transparency, behavior change technologies, positive and persuasive computing elements, and the use of drone technology for detailed thermal modeling. This illustrates the relevance and innovative contribution of our project. Our project integrates and investigates the interaction of these research approaches in a smartphone prototype to offer a holistic solution to promote energy efficiency. By combining behavioral change technologies, positive computing, and XAI, we aim to develop a target group-oriented system that not only motivates people to make energy-efficient decisions but also creates trust and understanding through explanations.

3 METHODOLOGY

Our research methodology aimed to develop a comprehensive understanding of the needs and challenges faced by our target groups to create an effective and user-friendly app prototype for energy efficiency advice. We employed qualitative research methods to achieve detailed insights, including interviews, empathy maps, affinity diagrams, and workshops. All participants were fully informed about the purpose and scope of the study and provided written consent to participate.

3.1 Participant Selection

We selected participants through network canvassing to ensure diversity in profession, and experience. The participants included tradespeople, who are experts in building construction and insulation; homeowners and tenants, who have varying degrees of knowledge about energy efficiency; energy consultants, who are professionals advising on energy-saving measures; and a drone pilot, who is a professional from the fire department with expertise in thermographic imaging. A total of seven interviews were conducted, with participants aged between 26 and 67 years.

3.2 Data Collection

3.2.1 Semi-Structured Interviews. We conducted semi-structured interviews to gather in-depth qualitative data. A structured interview guide was developed to ensure consistency across all interviews. The guide included technical questions tailored to each participant group. Each interview lasted approximately 30 minutes. The interview guide was developed based on an initial literature review and consultations with experts in the field. All interviews were recorded with participants' consent and transcribed verbatim for analysis.

3.2.2 Empathy Maps and Affinity Diagrams. After the interviews, the data were analyzed using empathy maps and affinity diagrams [14] to identify common themes and insights. Empathy maps served as visual tools to capture users' experiences, needs, and pain points, while affinity diagrams were used during workshops to categorize and cluster themes from the interview data.

3.3 Data Analysis

We employed thematic analysis as outlined by Braun and Clarke [7] to identify patterns and themes within the qualitative data. Recognizing the diverse levels of technical expertise among participants, the thematic analysis process accounted for different levels of familiarity with energy efficiency concepts and AI-driven recommendations. Additionally, the principles of Explainable AI (XAI) guided the coding and thematic generation, especially in identifying participants' needs for transparent and accessible AI-driven suggestions. This approach was integral in refining app features that prioritize user comprehension and trust.

3.4 Workshops

An affinity workshop [14] was conducted to consolidate diverse perspectives and develop key themes. The outcome of the workshop was the identification of functional requirements and design principles for the app. To ensure that all categories were relevant to the app's development, discussions focused on aligning each requirement with the app's functionality.

Following the affinity workshop, a "Wall Walk" [14] was conducted to translate insights into concrete design and functional decisions. Participants in this workshop included researchers and practitioners from related fields. Activities during the workshop involved discussion and brainstorming sessions to refine app features and usability.

3.5 Key Findings and Integration

The findings from the thematic analysis and workshops were integrated into the app's design and development process. The insights gained from the affinity diagrams were further explored in the "Wall Walk" involving other researchers from the field of human-centered technology development. Here, ideas and concepts were developed that served as the basis for the functional scope and design of the app. The discussions in the workshop helped to translate the insights gained from the interviews and analyses into concrete design and functional decisions.

The table below summarizes the key points derived from the affinity diagrams, highlighting the main insights from each participant group.

3.6 Integration and Analysis of User Perspectives

In our research, we specifically integrated a wide range of perspectives in order to develop a comprehensive understanding of the requirements for our app. The results from interviews with tradespeople, homeowners, energy consultants, and drone pilots paint a multi-layered picture of the needs and challenges in the field of building energy efficiency.

An important topic that tradespeople and energy consultants alike point out is the importance of benchmarks and measured values such as U-values and lambda values. These technical parameters are crucial for assessing the energy efficiency of buildings. However, evaluating them is of course a challenge for laypeople. Tradespeople pointed out that windows and doors often represent weak points in building insulation, with incorrect ventilation, for example through permanently tilted windows, causing additional problems.

The skepticism of some tradespeople regarding the effectiveness of apps in the area of energy efficiency became clear. They expressed concerns that end users may have difficulty using such technical aids effectively. In contrast, homeowners saw the app as a valuable tool for obtaining centralized information on energy efficiency and funding opportunities.

Discussions with drone pilots revealed legal and practical challenges in using drone technology, particularly in populated areas. Despite these challenges, they recognized the potential of drone technology for energy efficiency, although the limitations of the technology, such as the resolution of thermal images, were addressed.

All groups interviewed emphasized the growing relevance of energy efficiency, driven by rising energy costs and climate change. The need for individual solutions was emphasized, with tradespeople and energy consultants specifically pointing out the individual nature of the problems in different buildings.

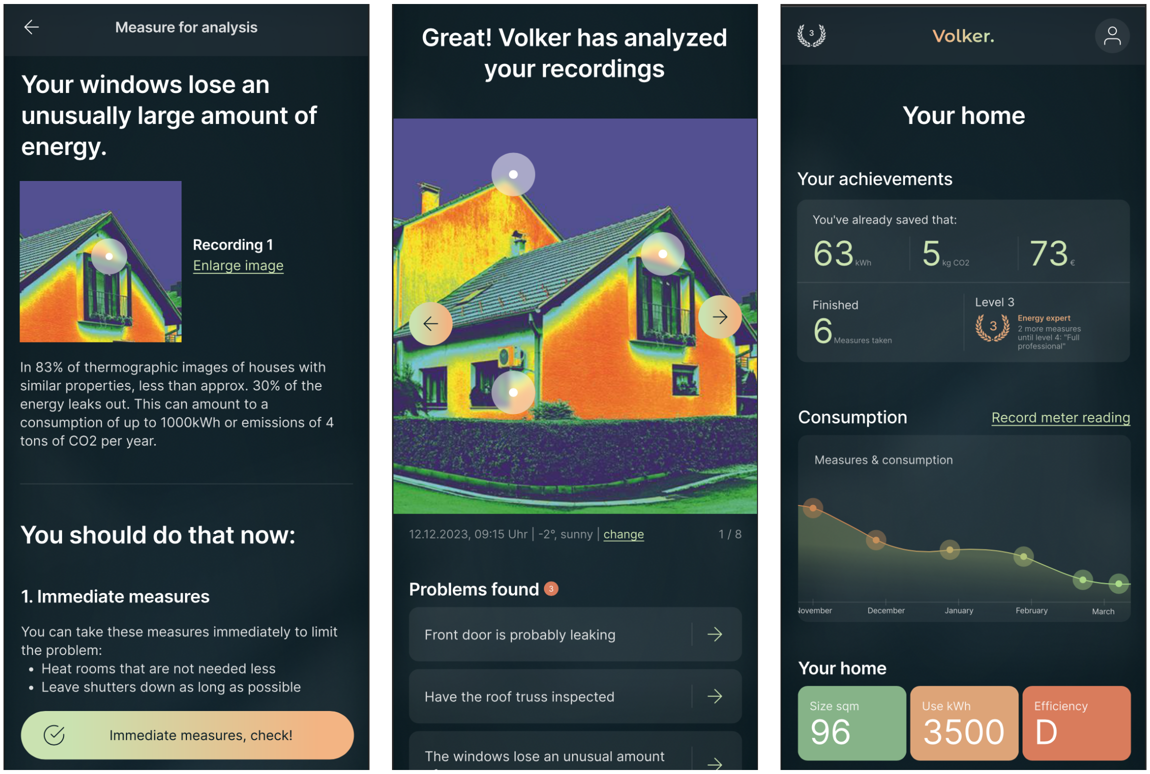
From these diverse perspectives, important conclusions can be drawn for the development of our app. Firstly, the app must be intuitive and easy to understand in order to appeal to a broad user base and be effective. Secondly, the app should be able to translate complex technical data into simple, actionable information. Thirdly, the integration of drone technology is promising, but requires careful consideration of legal and practical aspects. Finally, the emphasis on the individual requirements of each building underlines the need for a flexible and customizable solution that takes into account different user needs and building characteristics.

Category	**Key Points**	**Groups**
Benchmarks and Measurements	U-values as benchmarks, lambda values for materials, importance of measurable and understandable units for end-users.	Tradespeople
Craftsmanship	Decreasing construction demand, potential of app to directly lead to orders.	Tradespeople
Common Problems	Weak points in insulation often at windows, doors, and extensions; incorrect ventilation adds to the problems.	Tradespeople
Heating	Misconceptions about thermostat settings, obstacles to heating efficiency like furniture blocking radiators.	Tradespeople
App-related Skepticism	Skepticism about the effectiveness of apps in energy efficiency; potential confusion for end-users.	Tradespeople, Energy Consultants
Old Buildings	Challenges with old buildings like un-insulated attics, single glazing; importance of state-of-the-art standards.	Tradespeople
Drone Technology	Legal and practical challenges in using drones; potential yet limitations of drone technology in energy efficiency.	Drone Pilot
Motivation for Energy Efficiency	Acknowledgment of increasing relevance of energy efficiency due to rising energy costs and climate change.	All Interviewees
Energy Efficiency Consulting	Varied qualifications of energy consultants; potential of app for better consultant matching and documentation.	Tradespeople, Homeowners
Problem Detection	Individual nature of each building; use of thermography in problem detection; importance of visual inspection.	Tradespeople, Homeowners, Drone Pilot
Sustainability Concerns	Customers value less waste, energy efficiency as a trending topic; importance of ecological footprint.	Drone Pilot, Homeowners, Tradespeople
Expectations of the App	App as a problem identification tool; can't replace manual expertise; potential as a consultant's assistant.	Tradespeople, Homeowners, Energy Consultants
Cost Considerations	Balancing cost and benefits; importance of clarity on expenses; potential high costs of renovations.	Homeowners, Tradespeople
User Preferences	End-users' need for a desktop app option; privacy concerns; ultimate decision-making remains with the homeowner.	Homeowners, Energy Consultant, Drone Pilot

Table 1. Summary of Key Points from the Affinity Diagram, highlighting app-relevant themes

4 PROTOTYPE DEVELOPMENT AND INTEGRATION OF RESEARCH FINDINGS

The design of the prototype is based on the comprehensive insights we gained from the interviews and workshops, ensuring that the app effectively addresses the users' needs and challenges. The prototype follows principles of material



Your windows lose an unusually large amount of energy.

In 83% of thermographic images of houses with similar properties, less than approx. 30% of the energy leaks out. This can amount to a consumption of up to 1000kWh or emissions of 4 tons of CO2 per year.

You should do that now:

1. Immediate measures

You can take these measures immediately to limit the problem:
- Heat rooms that are not needed less
- Leave shutters down as long as possible

Great! Volker has analyzed your recordings

12.12.2023, 09:15 Uhr | -2°, sunny | change

Problems found 3
- Front door is probably leaking
- Have the roof truss inspected
- The windows lose an unusual amount

You've already saved that: 63 kWh | 5 kg CO2 | 73 €

Finished 6 Measures taken

Level 3 Energy expert 2 more measures until level 4: "Full professional"

Size sqm 96 | Use kWh 3500 | Efficiency D

(a) Dashboard with energy efficiency information and user interactions

(b) Display of thermographic imaging and identification of thermal bridges

(c) Analysis and gamification elements to encourage energy-efficient behavior

Fig. 1. Various aspects of the app prototype for enhancing energy efficiency in residential buildings.

design to ensure a simple and intuitive user interface, which is crucial for broad user acceptance, especially among less tech-savvy individuals. Wireframes were created based on simulated usage behavior of a first-time user and served as a concrete blueprint for the prototype development.

4.1 Functions of the Prototype and Relation to Positive and Persuasive Computing

The prototype allows users to create a fictitious user account and explore various functions of the app. A central feature is the dashboard, which displays critical information such as energy efficiency metrics and consumption curves of the house. Users can upload and evaluate thermal images and receive specific renovation suggestions based on the analysis. Although future plans include creating a thermal living space model using images from drones or handheld cameras, the current prototype assumes that existing images will be uploaded.

4.1.1 Dashboard and User Interaction. The dashboard is designed to provide users with a clear and comprehensive overview of their energy consumption and efficiency metrics. This includes interactive elements that allow users to engage with the data and gain insights into potential areas for improvement. Additionally, the analysis results are designed to be easily interpretable to build trust in the app's recommendations and to provide users with clear, understandable explanations of each suggested measure, reflecting principles of Explainable AI (XAI).

4.1.2 *Thermographic Imaging and Thermal Bridges Identification.*

Users can upload thermal images, which the app analyzes to identify thermal bridges and other inefficiencies. This feature is critical for providing actionable insights into where improvements are needed. Future enhancements will include integrating drone-based thermographic imaging for a more detailed analysis.

4.1.3 *Positive and Persuasive Computing Elements.*

Particular attention was paid to the integration of positive and persuasive computing aspects. To create a relatable and personalized user experience, the app communicates in the style of a seasoned craftsman named "Volker," giving users the feeling of being guided by an expert. The name "Volker" was chosen due to its commonality among skilled craftsmen in Germany, making it recognizable and familiar, especially for users who might prefer a straightforward and pragmatic communication style. The app's check function for completed measures and the progress diagram in the "My home" section reward users for successfully completing renovation measures, motivating them to continue using the app. These elements are designed to encourage users to implement energy-efficient measures, fostering a sense of self-efficacy [4] by providing them with actionable, understandable insights they can confidently act upon.

By allowing users to track their progress and rewarding them for each completed measure, the app also aims to satisfy the basic psychological needs of autonomy and competence, as outlined in self-determination theory [24]. Through these mechanisms, "Volker" seeks not only to facilitate energy efficiency but also to promote long-term engagement and motivation.

4.1.4 *Knowledge Database and Volker's Tips.*

The app includes a comprehensive knowledge database and "Volker's Tips," offering users in-depth insights into energy efficiency and funding opportunities. The tips and explanations are crafted to reflect Volker's style, providing practical advice in a relatable way. These resources aim to empower users by helping them make informed decisions and develop a deeper understanding of energy efficiency.

5 EVALUATION

The evaluation of our app aimed to assess its compliance with user requirements, particularly regarding positive and persuasive computing. The app's usability, core functionalities, and influence on user motivation and acceptance were key evaluation criteria.

5.1 Methodology and Participant Demographics

The methodology comprised usability testing, the Thinking Aloud method, and quantitative evaluations using the System Usability Scale (SUS) and the Net Promoter Score (NPS). The SUS is a widely used tool for measuring perceived usability, providing a standardized score that reflects the ease of use and general user satisfaction with the interface. The NPS evaluates users' likelihood of recommending the app to others, serving as an indicator of overall user satisfaction and loyalty. A total of ten user tests (N=10) were conducted. The participant demographic included 80 percent male and 20 percent female, aged between 22 and 59, living in different housing situations (60 percent in rented accommodation, 40 percent in owned homes).

Person	Gender	Age	Type of Residence	Owner	Profession	TA	CC	EEC
1	M	26	Apartment	No	Mason	5	7	5
2	M	56	House	Yes	SAP Consultant	6	6	4
3	M	28	House	Yes	Reinforced Concrete Builder	4	6	4
4	M	22	Apartment	No	N/A	7	2	1
5	M	46	Apartment	No	N/A	2	7	5
6	M	38	House	Yes	Application Testing Specialist	6	5	2
7	F	27	Apartment	No	HR Specialist	4	4	3
8	M	55	House	Yes	Sales Manager	5	3	4
9	F	59	Apartment	No	Financial Officer	5	3	4
10	M	26	Apartment	No	Student	7	6	3

Table 2. Demographic characteristics and self-assessment of technology affinity (TA), craftsmanship competence (CC), and energy efficiency competence (EEC) of the participants.

5.2 Results of the Evaluation

The participants rated the visual appearance and the basic operation of the UI elements predominantly positive. They particularly highlighted "Volker's tips" and the analysis function of the thermographic images, noting that the simple communication style felt relatable and accessible, especially for participants with a craftsmanship background. The structure of the measures and the "check function" were positively received and contributed to motivation, underlining the strength of persuasive computing. The overview with savings progress was perceived as particularly motivating, reflecting the principles of positive computing and fostering users' sense of control over energy-saving measures, enhancing their self-efficacy [4].

Critical feedback concerned the lack of transparency in the use of data, incomplete data collection on the home, and insufficient transparency in the assessment of energy efficiency. Users wanted clearer explanations and context for data and calculations, emphasizing the need for transparency as outlined in Explainable AI (XAI). The display of "experts nearby" caused mistrust regarding costs, and there was a desire for more transparent price information. Quantitative evaluations resulted in a SUS value of 83.25, indicating high usability, and an NPS of 50, suggesting good overall satisfaction with areas for strategic improvement.

5.3 Suggestions for Optimization and Conclusions

The evaluation indicates that more detailed information and more transparent explanations are needed for a more effective use of persuasive and positive computing. Suggestions for optimization include an improved presentation of data usage, more in-depth information on energy efficiency measures, and the inclusion of expert opinions. The check function and the presentation of the consumption curve should also be optimized to further promote user motivation and understanding. The integration of personalized recommendations and clearer visual feedback on progress could further enhance user engagement by addressing users' need for competence and autonomy, as outlined in self-determination theory [24].

Overall, the evaluation shows that the prototype provides a solid foundation, but further fine-tuning is needed to increase the effectiveness of the app in terms of positive and persuasive computing and to achieve a sustainable change in user behavior.

Table 3. Evaluation Results Linked to Persuasive and Positive Computing

Feature	**Positive Feedback (Persuasive Aspects)**	**Positive Feedback (Positive Aspects)**	**Areas for Improvement**	**User Suggestions**
Gamification Elements	High engagement with "Check" function, providing a sense of achievement	Enjoyment and motivation to continue energy-saving actions	Adjusting level ranking to be more appropriate	Implement a more nuanced reward system to maintain user motivation
Information Presentation	Clear structure and helpful thermography analysis	Understanding of energy-saving measures increased well-being	Need for clearer explanations of technical terms and calculations	Provide simple, yet detailed explanations to ensure understanding
User Empowerment	Users felt competent in making decisions based on app recommendations	Enhanced trust and perceived control over energy-saving measures	Some users felt overwhelmed by the amount of data presented	Streamline information and offer step-by-step guides for actions
Feedback Mechanisms	Immediate feedback on energy consumption was highly valued	Positive reinforcement through savings displayed in CO2 and monetary terms	Desire for more frequent and context-aware feedback	Integrate real-time feedback based on user actions to strengthen positive behaviors
Customization	The app's adaptability to different user needs was praised	Personalized experience improved user satisfaction	Need for greater personalization in recommendations	Develop an AI-driven personalized recommendation system that adapts to user behavior

6 DISCUSSION

Our research and development efforts have focused on aligning the "Volker" app with the actual needs of homeowners and residents of rental properties. This alignment is crucial for addressing the motivation, financial resources, and individual circumstances of users, as well as the specific characteristics of their housing. Our findings indicate that many current policy and market-led solutions do not sufficiently align with the everyday realities faced by most people and buildings. This misalignment results in a gap between policy initiatives and the practical feasibility of energy efficiency measures for the average citizen, ultimately affecting their effectiveness.

Our study builds upon existing research in the fields of energy efficiency, behavior change, and HCI. For instance, the work of Benavente-Peces [5] and Gabitov et al. [11] highlights the role of intelligent algorithms and sensors in improving energy efficiency. However, our research emphasizes that technological advancements alone are insufficient. As Boomsma et al. [6] and Pavlović & Barbaric [22] have shown, the application of thermographic technologies is effective in identifying heat losses, but these technologies must be made accessible and understandable to non-experts to be truly effective. Our findings support this by demonstrating the importance of user-friendly interfaces and clear explanations, as emphasized by Alsalemi et al. [2]. The application's design incorporates Explainable AI (XAI) principles [16] to provide users with accessible, transparent insights, fostering trust in AI-driven recommendations.

The integration of behavioral change technologies and psychological theories is essential for promoting energy-efficient behaviors. Our approach draws on the principles outlined by Fogg [10] and Thaler [1], who provide valuable insights into user motivation. By leveraging gamification elements, as discussed by Boncu et al. [29], our app engages users through interactive and rewarding experiences. This aligns with Bandura's self-efficacy theory [4], as users are empowered to take energy-efficient actions with confidence. Furthermore, the positive feedback and rewards are designed to satisfy users' needs for autonomy and competence, in line with Ryan and Deci's self-determination theory [24], which underscores the importance of intrinsic motivation in sustaining behavioral changes.

The use of Explainable AI (XAI) in our app addresses the need for transparency and traceability in AI decisions, as highlighted by McAreavey et al. [19] and Dey et al. [9]. By making the AI-based recommendations understandable to end users, we aim to increase trust and adoption of the app. This aligns with the findings of Alsalemi et al. [2], who emphasize the importance of understanding individual behavior patterns for effective energy solutions.

6.1 Practical Implications and Future Directions

The results of our project underscore the necessity of adopting a user-centered perspective in the development of energy efficiency technologies. Solutions must not only be based on theoretical models but also consider the real conditions and challenges faced by users. This user-centered approach is crucial for the successful promotion of energy efficiency, as it ensures that technologies are both socially inclusive and adaptable to different financial and lifestyle circumstances. Our findings reveal that the key to promoting energy efficiency lies in developing HCI solutions that are deeply rooted in the reality of users' needs. By providing transparent and user-friendly AI-driven recommendations, we aim to create trust and understanding, which aligns with the goal of fostering self-efficacy among users [4].

In summary, our research highlights the importance of aligning technological solutions with the practical needs of users. By integrating insights from related work and focusing on user-centered design, we can create effective and inclusive energy efficiency technologies. Future research should continue to explore the intersection of technology, behavior change, and user experience to develop comprehensive solutions that drive sustainable behavior and energy savings.

7 CONCLUSION AND OUTLOOK

This research demonstrates that user-centered, technologically advanced solutions can significantly enhance energy efficiency in residential buildings and effectively motivate users toward sustainable behaviors. The participatory development and evaluation of the "Volker" app prototype highlights the value of integrating positive and persuasive computing elements to actively engage users and foster long-term behavior change. Feedback from user evaluations confirmed that focusing on real-life conditions and user needs is crucial for the acceptance and success of HCI solutions, especially in addressing complex issues such as energy efficiency.

The evaluation also identified key challenges, including the need for greater transparency in data handling and more detailed information to support user understanding. These insights underscore the importance of Explainable AI (XAI) and user-friendly design in building trust and facilitating informed decision-making.

7.1 Limitations and Future Work

While our study provides initial insights into developing energy efficiency applications, it has limitations. The prototype remains at an early stage, with limited testing in real-world contexts. Additionally, the evaluation focused primarily on usability and short-term engagement, leaving long-term impact and behavioral retention to be explored. Future research should address these limitations by expanding the app's functionalities and assessing its effectiveness over time in varied demographics and settings.

Further prototype iterations will focus on enhancing functionalities and conducting broader testing with both technical experts and end users. Key improvements include integrating drone-based thermographic imaging for detailed thermal models and exploring additional sensors, such as humidity measurements, to improve recommendation accuracy. These advancements aim to bridge the gap between technical possibilities and user needs, moving the app closer to commercial viability.

7.2 Practical Implications and Research Contributions

Our research offers a foundational perspective on the role of HCI in promoting energy efficiency through user-centered AI applications. By providing transparent and accessible recommendations, we aim to build user trust and engagement, addressing psychological needs such as autonomy and competence, as outlined in self-determination theory [24]. Through such design, HCI solutions can foster intrinsic motivation and empower users to make informed decisions in line with their energy-saving goals.

This project underscores the value of an interdisciplinary approach to developing sustainable technologies that are technically feasible, socially acceptable, and adaptable to various lifestyles and financial contexts. Our findings indicate that user-centered design, transparency, and clear communication are central to the effective adoption of energy efficiency solutions.

7.3 Summary

In summary, our project highlights the potential of HCI solutions to drive sustainable behavior and improve energy efficiency in residential buildings. By focusing on user-centered design and incorporating positive and persuasive computing elements, we can create technologies that are both effective and widely accepted. Future research should continue to explore the intersection of technology, behavior change, and user experience to develop comprehensive solutions that contribute to addressing the challenges of climate change and rising energy costs.

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