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REVIEW

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The Potential of AI in Information Provision in Energy-Efficient Renovations: A Narrative Review of Literature

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Abstract

Energy-efficient renovation (EER) is a complex process essential for reducing emissions in the built environment. This research identifies homeowners as the main decision-makers, whereas intermediaries and social interactions between peers are highly influential in home renovations. It investigates information and communication barriers encountered during the initial phases of EERs. The study reviews AI tools developed within the EERs domain to assess their capabilities in overcoming these barriers and identifies areas needing improvement. This research examines stakeholders, barriers, and the AI tools in the literature for EERs. The discussion compares the functionalities of these tools against stakeholder needs and the challenges they face. Findings show that tools often overlook methodologies in human–computer interaction and the potential of textual and visual AI methods. Digital tool development also lacks insights from social science and user feedback, potentially limiting the practical impact of these innovations. This article contributes to the EERs literature by proposing an AI-supported framework and outlining potential research areas for future exploration, particularly improving tool effectiveness and stakeholder engagement to scale up the EER practice.

Keywords

AI; energy-efficient renovations; information and communication barriers; stakeholders

1. Introduction

Energy transition triggered by climate change is taking place in every carbon-emitting industry worldwide, following the UN Framework Convention on Climate Change pledges in the last decade (UN Framework Convention on Climate Change, 2015). As one of the most essential parts of anthropogenic climate change, the built environment is a key ecosystem that needs to go through an energy transition due to its impact on emissions. There are many pathways for decarbonizing the built environment, and one of the most prominent ones for Europe is renovating the existing built environment to create a more energy-efficient stock (European Commission, 2020). However, sustainable transitions are challenging and not linear pathways (Loorbach, 2010). Although several methodologies and tools are available in the construction sector to respond to the renovation challenge, collaboration between stakeholders is crucial for these to succeed (European Commission, 2024). As renovating the existing building stock requires the collective effort of various stakeholders, it is important to understand the stakeholders' needs and the barriers they face during Energy-efficient renovations (EERs). Much of the scientific research into EER tool development has addressed the technical challenges, and much less attention has been given to the challenges resulting from the collaborative nature of EERs.

It is important to investigate EERs holistically due to their multi-actor and multi-phase nature. EERs require many stakeholders to interact at various stages of renovation measures. The challenge is not only technical, relating to renewable energy sources and their integration into domestic energy systems, but also social, relating to the willingness and ability to adopt innovations and change behavior. Therefore, addressing socio-technical challenges through scientific research demands more than merely enhancing metrics, such as accuracy and speed, of existing methods; it requires a comprehensive approach considering the broader societal context. Scientific research may consider that individuals are not merely users but also actuators in practices, such as EERs (Reckwitz, 2002; Shove et al., 2012). Thus, the impact of the research for a support tool might be less effective without a deeper understanding of the design requirements for the developed tools (Brazier et al., 2018). The benefits of these approaches are that existing problems are investigated from many perspectives, from individual to societal.

Furthermore, EER processes also need policies and supply-side support to facilitate decision-making by providing information, financial subsidies, required technologies, and labor. The information type and how it must be communicated differs at each phase of the EERs (Prieto et al., 2023). However, the initial phase, where the decision-makers, such as homeowners, gather information and decide to proceed, is vital. This information-gathering stage (Arning et al., 2020) requires proper information provision and communication from trusted actors. This phase is followed by an acceptance phase where stakeholders try to gather information on existing solutions. The information discrepancy between the initial phase and the subsequent decisions in later phases can impact how occupants interact with their buildings (European Commission, 2024). On the other hand, research on AI gained momentum in energy studies where vast amounts of information can now be processed to organize, analyze, predict, and generate knowledge crucial for energy transition. This research focuses on AI tools to overcome information provision and communication barriers for EERs, emphasizing the early phases, key stakeholders, and the potential of AI tools developed, and aims to investigate these by asking: "What are the communication gaps in information provision and the potential of AI tools in ERR for key stakeholders?" We aim to find the gaps in current technological developments in AI, addressing the various stakeholders in the early phases of EERs. The recent developments in computing technologies and methods have also increased the amount of academic research on "machine learning" (ML) and AI to scale up energy renovations by developing decision support tools for stakeholders in energy renovations. Research into developing AI tools for energy renovations is diverse, and various barriers and stakeholders are investigated. However, the needs of every stakeholder at each phase are different. Therefore, this research aims to reveal the gap in the development of the EERs literature tool by mapping the key decision-maker and influential actor at the initial stage of the renovation with the developed tool in the literature by reviewing AI tools in energy renovations (Figure 1).

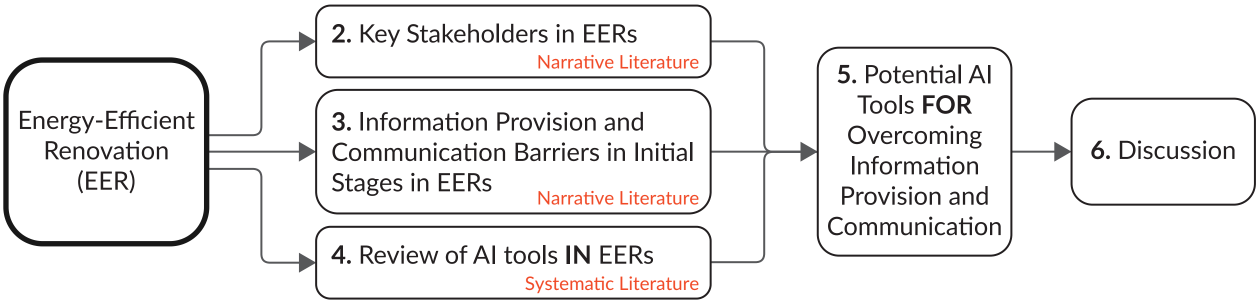

Figure 1. The flow of the article.

The article is divided into three sections to answer four linked research questions, mapping the findings to each other:

RQ1: Who are the key stakeholders in the decision-making of EERs?

RQ2: What are the information provision and communication barriers in the initial phases of EERs?

RQ3: What AI tools in EERs literature address users, features, and methods to overcome these barriers for stakeholders?

RQ4: What are the potential AI applications and methods from other fields to overcome information provision and communication barriers in EERs?

New developments in AI are also considered in the research scope due to the technical advances and the increasing number of research studies incorporating these methods in tool development for energy renovations. Furthermore, an expanding amount of AI-supported digital infrastructure is being implemented in many parts of digital environments and social platforms (see Section 5).

In Section 4, the existing reviews focused on energy prediction and benchmarking but often overlooked the social contexts of renovations. Seyedzadeh et al. (2018) compared ML methods for energy prediction and provided valuable benchmarks. Arjunan et al. (2020) did not specifically review the literature but compared ML models in energy benchmarking, which is one of the main decision-making factors of energy renovations, both from homeowners' and policy-makers' points of view. Gan et al. (2020) did not focus specifically on renovation challenges while reviewing the studies for energy consumption and carbon emissions. Wei et al. (2018) reviewed the data-driven energy analysis methods in the literature. Lygerakis et al. (2022) focused on ontologies used in buildings and various frameworks developed using knowledge graphs, and the part on occupants and the information exchange between stakeholders, pointing out the need for interactivity for end-users in decision-making. Roman et al. (2020), on the other hand, reviewed the artificial neural networks in metamodels on energy performance simulations. Shariq and Hughes (2020) review the state-of-the-art methods in building inspection for energy demands and their review reveals the importance of vision-oriented AI models to audit buildings. Lately, Yussuf and Asfour (2024) reviewed the literature on energy efficiency and AI, where they also focused on the applications of AI in many energy-related phases of the building lifecycles.

Other reviews, like those by Guyot et al. (2019), who reviewed artificial neural network applications in the building energy sector, and Grillone et al. (2020), who provided insights into energy prediction techniques and showed relevant themes but did not fully focus on stakeholders in renovations. The studies by Abdelrahman et al. (2021) on bibliographic natural language processing (NLP) analyzed the literature, and Deb et al. (2021) offered methodological insights, which are not fully aligned with EERs. Alrobaie and Krarti (2022) focused on model verification methods, reviewing only a randomized selection of the literature. Anastasiadou et al. (2022) conducted a bibliometric analysis that revealed findings but did not focus on renovations. This review highlights a need for research that bridges the gap between technological EER-related research and specific renovation practices, emphasizing the need for stakeholder-oriented analysis.

While the primary focus of reviews in this field has largely been on ML and AI methods for energy prediction and benchmarking, there is a need for more literature on energy renovations and how this research connects with stakeholders. Our research expanded to include reviews on renovations and their early stages, intelligent systems, and building interactions to enhance energy efficiency. Seddiki et al. (2021) identified significant gaps in tools developed in grey literature, especially the lack of user preferences in the web-based tool literature, which is vital (Seddiki et al., 2021). This review also highlighted the lack of financial information and step-by-step guidance in existing tools. Nielsen et al. (2016) explored early-stage renovation tools primarily utilized by professional building owners but noted difficulties due to the predominance of offline tools. Ferreira et al. (2013) analyzed decision-making tools for refurbishment, pointing out that although their study was slightly outdated, the fundamental gaps in stakeholder focus remain relevant. Day et al. (2020) examined building-human interfaces and their impact on energy efficiency, stressing the importance of interface design for better communication.

The reviews suggest that the linkage between stakeholders and AI-powered tools in the context of building renovations is insufficiently explored, particularly concerning user definitions and information interfaces. This shows the need for research that not only investigates these tools but also integrates stakeholder feedback and requirements to create an impact on renovation strategies.

The article is divided into six sections. Section 2 investigates the stakeholders in energy renovations, their power in decision-making, and the influencers. Section 3 delves into the barriers in the early stages of energy renovations. Section 4 reviews the AI tools in energy renovation literature. In Section 5, we cross-discuss the gaps in the literature and the AI tools that have the potential to be implemented in EERs literature. Lastly, Section 6 proposes a framework to steer future research trajectories in AI, EERs, and sustainability transitions for information provision and communication.

2. The Key Stakeholders in Energy Renovation

Energy renovations are multi-stakeholder processes involving property owners, designers, contractors, energy companies, urban planners, policy-makers, and others with niche roles. The research on these stakeholders, their roles, and their impact has been getting more attention in the last decade. The research to define key stakeholders matters due to the slow renovation rates all around the globe, especially in the Netherlands, where the goals are set higher than those of other European nations (Ministrie van Economische Zaken en Klimaat, 2019). Sebi et al. (2019) also mention the goals set by other developed countries and the policies to drive homeowners to renovate their properties, these even include mandatory actions such as requiring an Energy Performance Certificate in France or using renewable energy sources in Germany. However, the financial incentives and the fiscal policies to support these renovation actions require delicate adjustments due to the growing inequalities in homeownership and renovations (Fernández et al., 2024).

For example, there are three types of housing in the Netherlands: social housing, rental market, and homeowners. According to Klimaatakkoord, the number of houses to be renovated by 2030 is around 1.4 million, and almost half comprises homeowners (Broers et al., 2022). Homeowners are among the main decision-makers concerning home renovation (Laguna Salvadó et al., 2022). This shows that addressing homeowners as the key stakeholders has a potentially high impact on the practice. However, homeowners do not decide on the renovations by themselves. Their peers or other actors influence them in the renovation ecosystem (de Wilde & Spaargaren, 2019; Mogensen & Gram-Hanssen, 2023). Addressing the most influencing factors is also important to understand the links between the stakeholders.

Intermediary actors are important stakeholders in the EER process due to their ability to curate knowledge, tailor complex information for homeowners, and influence their decisions (Bertoldi et al., 2021; de Wilde & Spaargaren, 2019). Therefore, decision-making in EER is affected by influencing actors; in this sense, it is vital to understand their roles. Intermediaries are key influencers in the early phases of renovation and ensure trust with decision-makers. However, the social environment also plays a role in EER decision-making (Ebrahimigharehbaghi et al., 2022). The social interactions and the individuals who went through the EER process affect homeowners' decisions or their awareness (Mogensen & Gram-Hanssen, 2023). This interaction also points out the importance of social influence in energy renovation, where the information spreads with trust from peers and intermediaries.

Social influence is one of the key elements in energy transition. Social norms and individual interactions greatly influence the decisions made by homeowners (de Vries, 2020). Therefore, one of the barriers in the literature on information is the reliability of the sources and the actor who brings it (Ebrahimigharehbaghi et al., 2022). Social influence also plays a role in digital platforms as well, where respected people from the community have the potential to influence a local community by sharing their experiences online (Kwon & Mlecnik, 2021). It is essential to bring awareness to homeowners, yet it is also beneficial to apply energy renovations at scale, such as in condominiums, neighborhoods, or even districts.

Scaling up the renovation project is the most efficient route to energy transition in the built environment and is needed to speed up the transition. Scale is vital for many factors, including financial, administrative, and carbon mitigation. As the scale goes up, the prices for construction and administration go down, and the support from the local governments increases as well (Mlecnik & Hidalgo-Betanzos, 2022). However, the participatory processes and their facilitation hinder scaling up the energy renovations due to personal conflicts, various motivations, and lack of coordination (Cirman et al., 2013; Mlecnik & Hidalgo-Betanzos, 2022). The intermediaries in energy renovation also focus on this challenge (Elgendy & Mlecnik, 2024). Despite the features and functions intermediaries provide, they have recently become one of the main topics in energy transition. This is due to the possibility of the actors' influence on policy-making (Janda & Parag, 2013) and the business potential they possess (Elgendy & Mlecnik, 2024).

Intermediaries are also the link between the supply-side and the demand-side. Intermediary actors connect homeowners, contractors, and other experts with the financial information needed (Boza-Kiss & Bertoldi, 2018). Therefore, their knowledge is not limited to expertise in energy renovation procurement but also extends to demand and bureaucratic aspects, where they have in-depth insights into what homeowners want, value, or dislike, and which financial tools to use. For example, the existing financial schemes from the Dutch government are various and they change based on the province, city, and neighborhood, thus they can be too complicated for many to apply (Uitvoeringsoverleg Klimaatbeleid Gebouwde Omgeving, 2023). Alongside the efforts from academia and the government, the energy renovation policy can benefit from the experience of intermediaries (Janda & Parag, 2013).

Our research pointed out that even though home and building owners are the main decision-makers, intermediaries and social interactions are the key influencing factors. However, the decision-making phase is important when addressing these stakeholders. In residential EERs, the main decision-makers are the homeowners (Laguna Salvadó et al., 2022); however, in the initial phase, homeowners are open to influence from actors such as intermediaries or peers in EER decisions. Section 3 investigates the barriers in the early stages of information and communication, focusing on the actors mentioned in this section.

3. Information Provision and Communication Barriers in Initial Stages in Energy Renovation

The research defined various phases in EERs, such as an awareness phase (Arning et al., 2020), an information search (or orientation) phase, a design and planning phase, and an implementation and monitoring phase (Konstantinou et al., 2021; Prieto et al., 2023; Sequeira & Gouveia, 2022). The early stages of decision-making for EERs are also mapped, and the stakeholders differ there in their influence (Laguna Salvadó et al., 2022), yet in homeowners' case, the intermediary actors play an essential role due to their ability to craft information and communicate it well (Decuypere et al., 2022).

There is research about the barriers in EERs, and some of them even have specific focuses on the scale of the renovation, ownership of the buildings, and government policies (de Vries et al., 2020; Johansson et al., 2023; Klöckner & Nayum, 2016; Prieto et al., 2023). Furthermore, context-specific research is vital in the renovation practice due to the difference in enablers and cultural norms (Ebrahimigharehbaghi et al., 2019; Jia et al., 2021; Mogensen & Gram-Hanssen, 2023). There are various categorizations of barriers in the literature from individual to institutional levels. At the individual level, some significant barriers arise due to the financial burden of EERs, such as investment costs (Bertone et al., 2016; Jensen et al., 2013; Yang et al., 2021) or transaction costs (Ebrahimigharehbaghi et al., 2019). For example, in Germany, individually planned and subsidized renovation plan policies can support citizens with subsidies to encourage them to apply deep renovation measures to their homes based on the individual application plans (Directorate-General for Energy et al., 2020). However, the financial tools to apply these strategies were found to be biased (Fernández et al., 2022), and the information to use these subsidies is too complex to navigate for citizens (de Vries, 2020). A simplification of the bureaucratic process would ease the access to financial funds of the homeowners (Pérez-Navarro et al., 2023).

Moreover, information complexity is not just limited to financial tools but also includes building information, renovation technologies, and the renovation process itself (Jia et al., 2021). The information on the EERs can be complicated for people without expertise in the field (Arning et al., 2020; de Wilde, 2019, p. 19). Information about the existing building can also determine the EERs, where the physical properties of the building can be hard to renovate (Cirman et al., 2013; Long et al., 2015). Furthermore, the amount of information can be overwhelming and result in procrastination of the action, which hinders the renovation rates (de Vries, 2020). Tools such as the Energy Performance Certificates can enhance the understandability of the building's energy measurements and consumption by providing homeowners and tenants with simple energy labels, thereby influencing their decisions to renovate their properties (Charalambides et al., 2019). Furthermore, Building Retrofit Passports aim to enhance interoperability and facilitate long-term renovation planning for homeowners, policy-makers, and intermediaries, such as architects, by organizing the building information into a digital logbook (Gómez-Gil et al., 2022). Despite their benefits and the mandatory practices in the EU, even Energy Performance Certificates are still found to be too technical and need improvement to be more user-friendly (Zuhaib et al., 2022), and Building Retrofit Passport is still a new tool to implement in the built environment and requires further practice.

The barriers in EERs are different at every stage of the process. Early stages are the awareness and information collection stages (Arning et al., 2020; Klöckner & Nayum, 2016; Konstantinou et al., 2021), followed by the stages of audits, planning, and concept designs, which require homeowners, designers, and constructors to communicate. In these stages, communication and coordination issues in EERs are among the most mentioned barriers in the literature (Prieto et al., 2023). The complexity of the implementation of EERs (Ebrahimigharehbaghi et al., 2022), the administration of the process (G. Liu et al., 2020), or not being able to participate in the decision-making process in multi-stakeholder settings due to a lack of knowledge (Xue et al., 2022).

The research about the information provision barriers, how it is communicated, and the communication between the actors at different stages of the renovation process becomes prominent. The various stages and scales in energy renovations require different information to be communicated based on the stakeholders involved in the process, yet information communication is essential (Johansson et al., 2023; Prieto et al., 2023). From the homeowners' perspective, even being aware of the need for renovation is a step where the initial ideas start (Arning et al., 2020). Furthermore, awareness of energy renovations plays an important role in initiating audits (Palmer et al., 2013). The role of information provision and communication in the initial step, where understanding the needs of stakeholders, raising awareness, and then focusing on the understandability of the information, are essential.

The previous section, and this one, have provided the contextual background on energy renovation, including barriers, key stakeholders, and potential points to focus on to increase the speed of energy transition; these two sections also tried to answer the first and second RQs. However, in Section 4, this context will help link state-of-the-art methods with barriers, stakeholders, and potentials in the literature by reviewing the existing tools using AI for energy renovations.

4. Review of AI Tools in EERs

In this section, we explain the methodology of the review and the findings. This review section aimed to investigate the AI tools developed to support energy renovations or similar topics in the built environment, such as energy renovation-related policy support or energy performance certificates, to understand their relation with the stakeholders, and the barriers in EERs research in the literature. Therefore, the keywords in the review were scoping four sets of words, including the action(renovations), the context (building or housing), the technique (AI), and the purpose (energy efficiency). Since the word “buildings” may not represent all the types of buildings, we also added “housing” and included other residential studies such as social housing and housing policies. The technical keywords were limited to AI and ML since any other method is a sub-research field of these two. Our primary scoping keywords included “built, building, housing,” “energy,” “renovation, retrofit, refurbishing,” and “AI, ML.” These terms were used to search through Scopus, Web of Science, and ScienceDirect databases and search engines to ensure comprehensive coverage of the existing research in these areas on 9 February 2024 (see Figure 2). The review included all the indexed publications except the review articles because their research methods were on analyzing the literature rather than developing a tool.

In the first phase, we applied specific inclusion criteria to identify studies that explicitly mention using tools, platforms, or applications within the research outcomes to titles and abstracts. This includes any article that discusses developing or utilizing web-based services, interactive technologies, or those offering tailored or targeted information. Furthermore, the inclusion criteria required that the studies address the communication or involvement of specific actors or stakeholders within the field, excluding those that focus solely on processes, institutions, or non-interactive actions.

For the second phase, we applied exclusion criteria to refine the scope of our review further by reading the introductions and conclusions. A study was excluded if it did not discuss a specific tool or technological application designed for user interaction in the context of building and energy. This two-pass review process helped us focus on studies related to AI tools in energy renovations involving stakeholders. This approach also allowed us to analyze how AI methods are employed to enhance energy efficiency and user engagement in the building sector, reveal an overview of the current landscape, and identify gaps for future research.

This section aimed to understand the relationship between the main stakeholders in the literature, the main barriers in the early stage of EERs, and the AI tools. Furthermore, how the features, methods, and addressed users of AI tools help overcome the barriers in EERs literature. We discussed that homeowners are found to be the main stakeholders in decision-making, yet intermediaries and social relations are the most influential actors in Section 2. Furthermore, we mentioned in Section 3 that information and communication barriers are among the most prominent barriers in the early stage of the EERs. Therefore, we mapped the number of features and users addressed together in the studies reviewed and discussed them regarding the stakeholders and the barriers in previous sections (see Figure 3).

The findings from the review showed that there is a focus on speed or efficiency in computing, a graphical user interface, data provision for renovation, and user data input in features (see Figure 3). Only a quarter of the studies inherit features that can support the information in visual formats, such as graphical user interfaces and visualization. The visual interface elements help represent complex information, yet there are only 11 studies

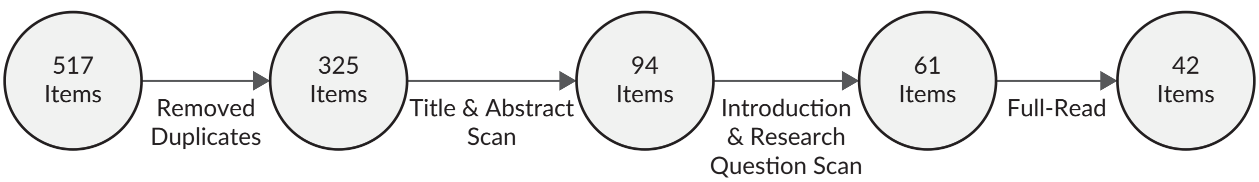

Figure 2. Review process chart.

Row Labels	Architects / Designers	Home / Building Owners	Stakeholder	Non-Technical	Facility Managers	Public/Local Authorities	Policymakers	Industry	Urban Planners	Contractors	Experts	Decision-Makers	Builders	Citizens	Researchers	Consultants	Auditors	Residents	Developers	not Specified	Buyers	Tenants	Spesific Software Users	Engineers	Energy-Saving Institutio	Remodeler	End-user	Portfolio Managers	Energy Decision-Makers	Real-estate Enterprises	Investors	Asset Holders	Technicians	Wall designers	Planners	Households
Interface Design	6	3	3	1	3	2		1	1	2	2		1	1		1	1	1	1	1				1			1	1			1	1	1			
User Inputs	9	4		2	1	2		1	1	2	2	1	1	1		1								1		1							1			
GUI	5	3	3	2	1	1		1		2	2		1										1			1	1							1		
Fast	3	1	2	2			3	1				2		1	1					1	1	1	1	1	1					1						1
Data for Renovation	2	3	2	1	3	1			1	1	1	1	1			1	1	1	1	1							1									
Scalable	2	2	1	1	1	2	3	1	3			1			1	1																				
Automation	4	2	1	2		1	1	1	1		1				1					1					1					1						
Visualization	2	1	2	1	1	2	1	1	1					1	1																					
User Interaction	2	1	1	1	1					2	1		1	1			1	1	1																	
LCC / LCA	2		1	1	1							1																1	1		1	1			1	
More Accurate			1		1		2	1	2											1	1	1							1							
User-Friendly	1	1		1	1					1	1		1				1	1	1																	
Immersive	1	1			1					1			1				1	1	1																	
Real-time Data Analysis	1	1	1		2	1			1							1																				
Real-time Feedback	2	2	1			1		1				1																								
Prediction		1	1	1			1					1									1	1		1												
Robust Learning Model for Prediction					1		2	2	1						1														1							
Building Monitoring	1	1	1		2	1			1							1																				
Online Connection	1	1			1					1			1				1	1	1																	
Digitalization	1	1			1	1			1			1				1																				
Easy	1		1	2																	1	1	1													
Information Provision		1		1		1		1			1	1		1																						
Tailored Information		1		1		1		1													1	1														
More accessible tool	1		1	2							1												1													
Time Effort	1					1		1	1						1																					
Understandable	2	1										1		1																						
Understanding Moisture Durability	1									1			1													1								1		
Summarization			1				1																		1					1						
Interoperability	1			1						1	1																									
Transferable			1	1								1																								
Historical Buildings																												1			1	1				
Bottom-up			1				1		1																											
Privacy		1				1		1																												
Social Influence		1				1		1																												
Exergy Analysis							1	1							1																					
Spatial			1				1		1																											
Mobile Ready				1								1																								
Step-by-Step										1	1																									
Material Database	1																																			
Optimizing EPC														1																						
Supply Integrated	1																																			
Interactive			1																																	
Explainable	1																																			

Figure 3. Features (right column) and users (top row) are addressed in the literature. Note: The coding is based on the definitions by the authors of the reviewed articles.

that applied a method to define design requirements or validate the tool by gathering feedback based on the design prototype. This shows a lack of focus on user-centric tool development research.

Moreover, only 19 of 42 studies provide features critical for user-friendliness and effectiveness, such as explainability, interactivity, step-by-step guidance, summarization, understandability, and ease of use. Only a few studies have combined these features with an interface design and visualization, pointing out a significant area for improvement. Although 10 out of the 42 studies mentioned collecting feedback through workshops, interviews, and surveys, only two did so before the tool's development. The remaining studies conducted validation exercises in post-development, pointing to a potential gap between tool design and end-user needs.

Although there were parameters included as "social," these parameters were more focused on the users' comfort and preferences. However, we should note that only 15 out of 42 studies allowed user input;

despite allowing this interaction, the tools in the literature were not open enough to engage with the users. This finding also matches previous reviews (Seddiki et al., 2021), though the number of tools that allowed user inputs or preferences was more than the previous review on grey literature.

Demographically, the studies mention various user groups, with homeowners being the focus at 31%, design professionals at 38%, and policy and planning stakeholders at 21%. However, 36% of the studies vaguely reference general decision-makers or stakeholders, suggesting a lack of specificity in targeting user needs.

Of the 42 studies, only two utilized computer vision as a medium for AI. The reviewed literature has no research focusing on NLP to develop energy renovation tools. An additional literature search using the terms "NLP" and "LLM" rather than "AI" and "ML" further confirmed this gap, indicating an underutilization of these methods in scientific indices. Although studies use NLP to analyze the literature (Abdelrahman et al., 2021), the technique has not been implemented in the tool development.

Regarding decision-making support methods in the review, nearly a quarter of the studies investigated utilize multi-attribute optimization, multi-criteria analysis, multi-criteria decision analysis, multi-criteria decision-making, multi-objective optimization, analytical hierarchy process, and preference ranking organization method for enrichment evaluation. These methods facilitate cognitive decision-making processes by quantifying key decision factors, showcasing a robust approach to complex decision environments. However, visualizations can help ease decision-makers cognitive load (Padilla et al., 2018), yet these have not been considered in many studies. The studies in the review discuss different models, such as black-box (data-driven), white-box (physics-based), and hybrid models, which integrate both models and their advantages for use cases.

Despite existing tools for renovation practices, expertise, and policy, there is a lack of tools to inform policymakers using input from the stakeholders. The tools in the review do not mention connecting the stakeholders and policymakers in a scalable manner. Users' input through their interaction with EERs and policy-making is connected, yet the studies do not mention any form of connection between this practice and informing policy-making, especially in a scalable and explainable way for EERs.

Lastly, this review reveals a significant deficiency in tools designed for social influence. Tools focusing on homeowners, designers, and planners are common, yet those facilitating knowledge exchange among intermediaries for social impact are missing. Some studies mention the social influence aspect of the EER decisions; however, only one of the studies targets homeowners as the tool's users and implements UI and user feedback (B. Liu et al., 2023). This lack of integrated tools suggests that while many tools address several aspects of energy renovations, comprehensive solutions that integrate multiple perspectives, such as social influence and user-centricity, are still needed. The findings from the reviewed literature reveal the need for more interactive, user-focused, and integrated tool development in energy renovations.

5. Potential AI Tools for Overcoming Information Provision and Communication Barriers in EERs

In this section, we will discuss the stakeholders, barriers, and AI tools reviewed in the previous sections to reveal the gaps in the literature and the potential research trajectories to cope with the barriers in the literature for better tool-oriented research. We will discuss how to improve information provision and communication barriers to the main stakeholders using the methods mentioned in the reviewed literature and potential methods used in other fields to overcome similar barriers.

The tools in the literature are mostly being developed to improve the previous studies' accuracy, robustness, and scalability. While technical improvements are necessary for research, the literature on human–computer interaction, such as research-through-design (Zimmerman & Forlizzi, 2014), to improve the usability and application of these tools is missing. The tools developed in the reviewed literature also have complex systems, including societal, financial, political, and environmental aspects. However, there is no mention of methodologies such as complex systems engineering (Brazier et al., 2018). Even though the prototypes of the tools have been developed, the methods, such as design prototyping (Gero, 1990) or similar, are not mentioned. This gap also shows that tool development in EERs has not embraced methodologies for tool development for specific users despite the addressed users or stakeholders in the literature.

As Day et al. (2020) also suggest, the users' behavior greatly affects the usability and the impact of energy efficiency. The research on tool development for energy renovations must consider that user behaviors and lifestyle are important factors in the interaction design of the tools. The users' values can play an essential role in transitions and, therefore, the development of user-oriented tools. The research on social values and how they can motivate sustainable transitions is vital (Mouter et al., 2019). Furthermore, the methods to scale these value interpretations by computational methods have great potential as they can link the policy-makers with citizens (Mouter et al., 2021; Siebert et al., 2022).

Despite many studies mentioned in the literature on the acceptance of AI, and related trust issues such as black-box models (Kelly et al., 2023), meaningful human control is not mentioned in the reviewed literature. Concepts such as "explainable AI" or "hybrid intelligence" that help the stakeholders understand and control the models in a meaningful way were missing (Guszcza et al., 2022). This gap is important because AI systems are becoming more dominant in all fields, and their controllable scalability without biases is a vital problem.

The review showed that the tools are mostly not developed considering the social aspects of EERs. The influencing actors and the dynamics between these actors play an important role, and these dynamics can shape the renovation practice based on the local cultures (Camarasa et al., 2020). The research points out the importance of intermediaries in EERs and their influence on homeowners' decision-making for EERs (de Wilde & Spaargaren, 2019; Sequeira & Gouveia, 2022), as well as the influence of social interactions within homeowners' social circle (Ebrahimigharehbaghi et al., 2022). Kwon and Mlecnik (2021) suggest that online platforms sharing the experiences of locals through local authorities might influence the residents to consider EERs.

Moreover, in this perspective, NLP methods are not considered in the reviewed literature. The complexity of the information that might influence the decision-makers can be simplified and delivered to the users. There are studies used to gather information using NLP-based models in similar contexts (Zhang et al., 2023), or to simplify complicated large climate reports (Bingler et al., 2022). These developments also show us that AI methods in other mediums (text, sound, image, and video) can help increase the scale of interactions and information provision, thus facilitating communication in EERs.

One of the features of intermediary actors in EERs is tailoring information based on the needs of the stakeholders (Yang et al., 2021). This shows the impact of tailored information provision. Yet, the scalability of intermediary actors is limited due to their physical reach, such as information meetings or in-person conversations with stakeholders. However, the tools in the review do not account for this kind of scalability at all. The digital platforms developed by reliable actors such as local authorities and the information provision with input from the stakeholders using textual or visual AI models have great potential in scaling and keeping reliability together. This does not mean overriding the intermediary actors in the ecosystem, yet it is quite possible to augment their reach to more stakeholders by using EER-specific tools that have multi-modal information provision. These tools are embedded subtly in our lives as instant messaging apps or send emails using popular email service providers, and they can potentially improve our communication skills (Hancock et al., 2020). That includes the multi-stakeholder deliberations for multi-stakeholders (ACM Collective Intelligence Conference, 2022; Siebert et al., 2022), such as multi-owner buildings or district-scale energy renovation projects. The help of AI using visual models also applies to architectural design processes (Castro Pena et al., 2021) and deliberations over multi-stakeholder project designs or visuals (UrbanistAI, n.d.)

Our analysis has shown that the tools discussed in the literature have various features to address the challenges of EERs; however, the main stakeholders, such as homeowners and other intermediaries, still do not receive the required attention. This review has shown that AI tools insufficiently challenge the information and communication barriers at the early stages of energy renovations. Furthermore, there is a lack of focus on user input in the early development phase and, therefore, user-centric tool development. Lastly, the potentials of various AI models were not considered most of the time in the literature.

6. Discussion

In this section, we discussed the future trajectories in EERs research and the potential of AI to create an integrated and scalable ecosystem. This study aims to define the gaps in the EERs literature, focusing on AI tools, and tries to compare three perspectives (stakeholders, information barriers, and AI tool literature) in EER studies to find the potential AI methods that can be applied in EERs context to overcome the information provision barriers.

The EERs ecosystem is a complex system, and to tackle information barriers, we have to think about the problem in an interactive framework (see Figure 4). The framework is an experimental way to connect all individuals and institutions via an adaptive AI-supported interface. The results of the review and the potential AI methods to implement in the EERs context mention that the literature lacks social influence aspects, unscalable information tailoring, lack of human-in-the-loop perspective, and, lastly, the missing link between the stakeholders and policy-makers.

In the framework (Figure 4), we wanted to point out that all these aspects should be considered together in an integrated architecture. Here, five nodes are interconnected to each other via a central node. The "social influence" node is connected to the center to achieve a scalable information provision based on the needs of the "individuals" and gather the experiences from their EER experiences; moreover, this interaction aims to also deliver the information from other individuals to influence socially. "Integrated data platform" aims to collect, organize, and provide knowledge, such as policy, expert opinion, and successful projects in the

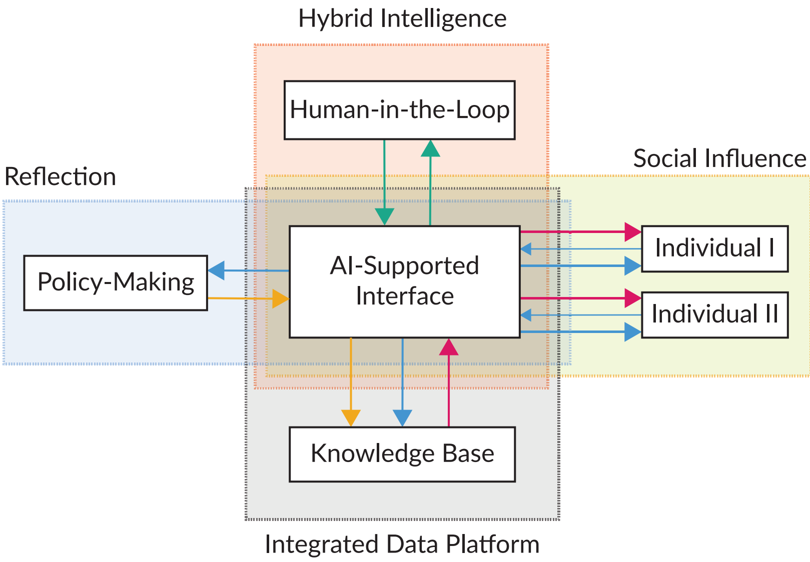

Figure 4. AI-supported interface framework.

"knowledge base," for the central node. "Reflection" is the node where insights from individuals, expert opinions, and policies are compared and reflected on for better "policy-making."

"Hybrid intelligence" is the audit part of the AI-supported interface framework where experts in the ecosystems intervene in the AI system as "human-in-the-loop" to improve the reliability of the central node. Lastly, the "AI-supported interface" aims to receive the information coming from all sides and deliver it to each node based on their queries.

Sustainability transition requires information delivery between different levels of management (Loorbach, 2010); from strategic to operational levels and back. The framework (see Figure 4) also considers the knowledge that affects the social influence with the practices that evolve and are disseminated by the mediums of communication (Shove et al., 2012). Studies that try to frame sustainability transitions help researchers understand the values, motivations, and meanings behind EER decisions, therefore helping them find the most impactful tool to develop.

For future research, it is crucial to understand that EERs are not solely technical processes but rather socio-technical transitions. This requires understanding the stakeholders, social challenges, and pathways to create impact at their intersection. This involves enhancing AI tools' technical specifications and ensuring they are designed with a thorough understanding of the socio-technical systems they aim to support. By addressing the current gaps in tool functionality and stakeholder engagement, the adoption of EERs can be accelerated. Further research on AI-powered tools can contribute to the broader sustainability goals and reduce environmental impact in the built environment.

7. Conclusion

This article investigated EERs in the built environment, focusing on the main stakeholders in decision-making and influencing, as well as the information and communication barriers at the initial stages the stakeholders encounter in renovation projects. In our review of AI tools supporting EERs, we identified gaps in methodologies and tool functionalities that align with the requirements of key stakeholders, particularly homeowners and intermediaries. While AI technologies offer promise for improving the decision-making process in EERs, there remains a strong need for tools that address information and communication barriers stakeholders face during the early stages of EERs.

The literature review highlights the lack of user-friendly, interactive tools that allow user input, step-by-step guidance, and stakeholder communication. The reviewed literature showed that the user-centric human–computer interaction methods to develop tools for targeted users were mostly not used. This gap points to the necessity for a multidisciplinary approach in tool development, integrating insights from social sciences to ensure digital solutions are grounded in the practices of stakeholder interactions and community dynamics in addition to the need for "stakeholder-oriented analysis." We proposed a framework to cover the literature gaps and explain the links and nodes that respond to these specific problems.

Furthermore, the research suggests the potential for other AI techniques, such as NLP and computer vision, to develop more tools to improve how information is communicated within the EERs ecosystem. Such tools could help stakeholders by simplifying complex textual and visual knowledge and making decision-making more comprehensive. Moreover, when needed, they can facilitate more interaction and information provision to different stakeholders at different phases of efficient renovation (European Commission, 2024; Prieto et al., 2023).

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Conflict of Interests

In this article, editorial decisions were undertaken by Neil Yorke-Smith (TU Delft, the Netherlands).

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

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