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Human-centered integration of small wind turbines in urban environments: a semi-systematic review from an industrial design perspective

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The increasing demand for renewable energy solutions, coupled with the urgent need to mitigate climate change, has positioned urban wind energy, particularly small wind turbines (SWTs), as a viable alternative for cities. This study aims to explore the socio-technical challenges and opportunities associated with the integration of SWTs in urban environments, emphasizing the critical role of design in addressing these challenges. Through a semi-systematic review of existing literature, we analyze the various factors influencing the acceptance and effectiveness of SWTs, including urban aesthetics, noise levels, safety concerns, and the democratization of energy technologies. We propose a comprehensive framework that incorporates human perspectives into the design process, advocating for interdisciplinary collaboration among designers, engineers, and social scientists. By engaging citizens as co-creators in the development of SWT solutions, we can better align technological innovations with the needs and values of urban communities. This participatory approach not only enhances the design quality but also fosters trust and acceptance among residents, ultimately contributing to a more sustainable energy transition. The findings of this research provide valuable insights, highlighting the importance of human-centered design in the successful implementation of renewable energy technologies in urban settings. By addressing the complexities of urban wind energy through a holistic lens, this study contributes to the ongoing discourse on sustainable urban development and the role of community engagement in shaping the future of energy solutions.

KEYWORDS

urban wind energy, small wind turbines (SWTs), human-centered design, renewable energy integration, socio-technical challenges, urban sustainability, industrial design, future cities

1 Introduction

The world is witnessing an urgent push for renewable energy solutions. Cities, major contributors to global energy consumption and carbon emissions, are at the forefront of this transformation and face a pressing need to transition to renewable energy sources. While solar energy has seen significant adoption in urban environments, wind energy faces unique challenges due to its potential impact on urban landscapes and human factors.

This research provides a novel interdisciplinary perspective by examining the integration of small wind turbines (SWTs) in urban environments through a human-centered design lens. While most existing literature focuses on technical optimization, our work bridges engineering and design disciplines by systematically analyzing how human factors are considered—or overlooked—in current research. The innovative contribution lies in identifying specific design strategies that can transform SWT adoption from a purely technical challenge to a socio-technical opportunity for community engagement and democratized energy production.

This study explores the potential of small wind turbines designed specifically for integration in buildings, focusing on the perspective of design as a key factor in overcoming urban-specific limitations. Current SWT solutions are analyzed through the lens of crucial factors for successful urban implementation: human-related factors. For instance, compact wind energy systems can disrupt urban aesthetics and the skyline of a city. This disruption goes beyond the point of view of citizens: The architectural value of a city is very important to its identity. Vibrations generated by wind installations can negatively impact residents' quality of life as both audible and non-audible frequencies are important environmental factors to consider. The risk of turbine blade detachment or similar accidents in densely populated areas raises safety issues. Traditional wind farms are often large-scale projects, limiting individual or community participation in energy transformation, and thus, in its democratization. Democratization of urban scale is determined by self-consumption. When consumers engage in self-consumption, they become aware of their daily energy consumption and habits (Gil-García et al., 2022). They discover that there are time periods of cheaper and more expensive energy and develop strategies to optimize energy surpluses. This awareness prompts consideration of storage options, such as batteries, or redirecting surplus to power electric vehicles or aerothermal systems. This process makes us owners of our energy, not just in the sense of purchasing it but in understanding and using it efficiently (Cousse et al., 2020). It positions humans as important actors in daily energy-related actions. By analyzing today's SWT proposals, comparing them to other energy technologies, and identifying gaps and opportunities, this study aims to identify relevant success factors for urban wind energy. This analysis focuses on the current situation of available solutions, paving the way for innovative and comprehensive products and proposing strategies that enhance the value proposition of urban wind power for the future. It takes SWT as an example of changemaker technology and reflects on the academic world's current approaches and future challenges. Exploring avenues for developing new comprehensive solutions to innovate and enhance the value of urban wind energy proposals is crucial for more livable cities.

In this study, we discuss the current state of wind energy and SWT technology, and the pivotal role of industrial design thinking in enhancing the viability and acceptance of these systems, to identify gaps and opportunities in current solutions. In Section 2, we analyzed literature and current proposals, considering factors directly relevant to cities and their residents. In Section 3, we present a semi-systematic review, centering on people living in urban areas, directly related to wind energy urban technologies and their relation with city inhabitants. In Section 4, we identify which success factors are not considered today and should be, in urban environments, for a fairer energy and social transition of our cities.

2 Context of urban small turbines: state of the art

Energy, in various forms, is an essential input for socioeconomic development and technological advancement. Without it, modern society would be unable to function as critical sectors rely on various energy forms to perform their tasks. According to 2022 data, fossil fuels dominate the world's energy sector, accounting for 80% of total consumption. Renewable energies, such as solar, wind, and hydroelectric energy, account only for 20% of total consumption (International Energy Agency, 2022a). The world's energy sector faces many challenges, such as energy security, equity, and sustainability. The transition to renewable energy is a complex challenge, but it is necessary to ensure a sustainable future for the planet.

Countries worldwide are advancing renewable energy to enhance energy security amid global geopolitical tensions. Governments and companies aim to reduce reliance on imports, driving innovation in energy technologies. Renewable energy is rising due to fossil fuel limitations, high prices, climate concerns, and technological advancements (World Economic Forum, 2023). Looking at the short term, a 60% increase in renewable energy is expected by 2025, which would lead to the improvement and price reduction of these technologies in the long term (International Energy Agency, 2022b). Global efforts to mitigate greenhouse gas (GHG) emissions are resulting in a surge in demand for renewable energy sources and advancements in low-carbon technological solutions (International Energy Agency, 2022a). Although the installation of SWT in buildings is growing at a low rate, the World Wind Energy Association (WWEA) confirms that the business is growing at 11.4% per year (World Wind Energy Association, 2023).

Advancing a fair and inclusive clean energy transition requires engaging diverse stakeholders—e.g., industry leaders, policymakers, labor representatives, youth, or communities—to ensure that socio-economic challenges are addressed and opportunities are equitably distributed. As the International Energy Agency (IEA, 2023) has emphasized in recent years, fostering dialogue among these groups is key to shaping energy policies that put people at the center of the transition.

2.1 The challenge of wind energy in urban areas

In 2013, 64% of energy consumption was concentrated in urban areas (World Economic Forum, 2023); today, more than 45% of the EU lives in urban areas and they account for a forecast energy demand of 85% by 2050 (IEA, 2023). Cities, accounting for less than 2% of the Earth's surface, consume 78% of the world's energy and produce more than 60% of GHG emissions (World Wind Energy Association, 2023).

It is important to discuss current energy supply systems in cities. In Spain, for example, the electricity transmission network has more than 34,500 km of high-voltage lines to deliver power to all populated areas. The total length exceeds 600,000 km, approximately 15 times the perimeter of the Earth. Electric energy is generally generated from the transformation of energy resources of fossil origin or renewable energy resources such as the sun, wind, water, biomass, or uranium in nuclear power plants, most of the time thousands of kilometers away from the points of consumption (Eriksson et al., 2008). As a counterpoint, public policies are being considered to promote the generation of local electric energy, where for example Spain's government has approved a Royal Decree-Law (RDL) that restricts the right to self-supply to two thousand meters (2 km) (Moreira Chagas et al., 2020) to make the process easier.

Since ancient times, civilizations have harnessed wind energy, later evolving into electrical applications during industrialization. Panemons, vertical-axis windmills dating back to the 10th century BC, were used in Central Asia for pumping systems and grinding grain. Some ancient designs, such as the Nashtifan mills in Iran, still survive today (Figure 1). Nowadays, cities and their inhabitants are considering the use of similar wind power systems for their benefit, even if their needs are different from thousands of years ago. It is being considered to put SWT in buildings to take advantage of their energy generation. The scientific development of urban wind energy products and markets has primarily focused on the challenges of harnessing wind in urban environments. Research in this area addresses obstacles related to building types, heights, locations, and urban geography, aiming to optimize wind use for electricity generation. Studies emphasize the importance of energy potential assessments and the integration of turbines into urban layouts (Koukofikis and Coors, 2024; Wang et al., 2022). Key challenges include understanding urban aerodynamics and simulating complex wind flows, often employing computational fluid dynamics (CFD) as a critical tool for accurate modeling (Ware and Roy, 2016; Wang et al., 2016).

Research indicates that high-rise buildings are particularly advantageous for wind capture due to their elevation (Figure 2), although variability in wind patterns can arise from surface roughness and surrounding structures (Hang-Hang Yang and Lei Song, 2012; Allegrini and Carmeliet, 2017). Despite the growing body of literature on urban wind energy, much of the focus remains on theoretical models and isolated case studies, highlighting the necessity for more comprehensive and integrated approaches to effectively harness this renewable resource in urban landscapes (Gagliano et al., 2012).

The classification of small wind turbines (SWT) based on their preferred locations in relation to buildings is an important aspect of urban wind energy research too. This classification can be categorized into several distinct types: rooftop installations, mounted beside or between multiple buildings, integrated within the building structure, and stand-alone turbines situated near the building. Each of these configurations has unique advantages and challenges, which can influence their efficiency and effectiveness in harnessing wind energy (Kwok and Hu, 2023; Park et al., 2015; Rezaeiha et al., 2020).

Current studies focus on optimizing SWT designs and their placement; however, much of the literature remains largely technical and isolated, lacking comprehensive integration (Toja-Silva et al., 2018). However, those studies are purely technical and theoretical works that expertise isolated works and are technocentric. Smart city visions remain firmly focused on solving sustainability problems from a human-centered and technocratic starting point, often ignoring the interdependencies of life (Clarke et al., 2019). Despite the increasing recognition of this need, interdisciplinary research projects remain a minority within the broader scope of energy research. Such

FIGURE 1
Vertical mills or Persian panemons (Nashtifan, north-eastern Iran). This vertical axis wind design is at least 3,000 years old. Attribution: Hadidehghanpour, CC BY-SA 4.0, via Wikimedia Commons.

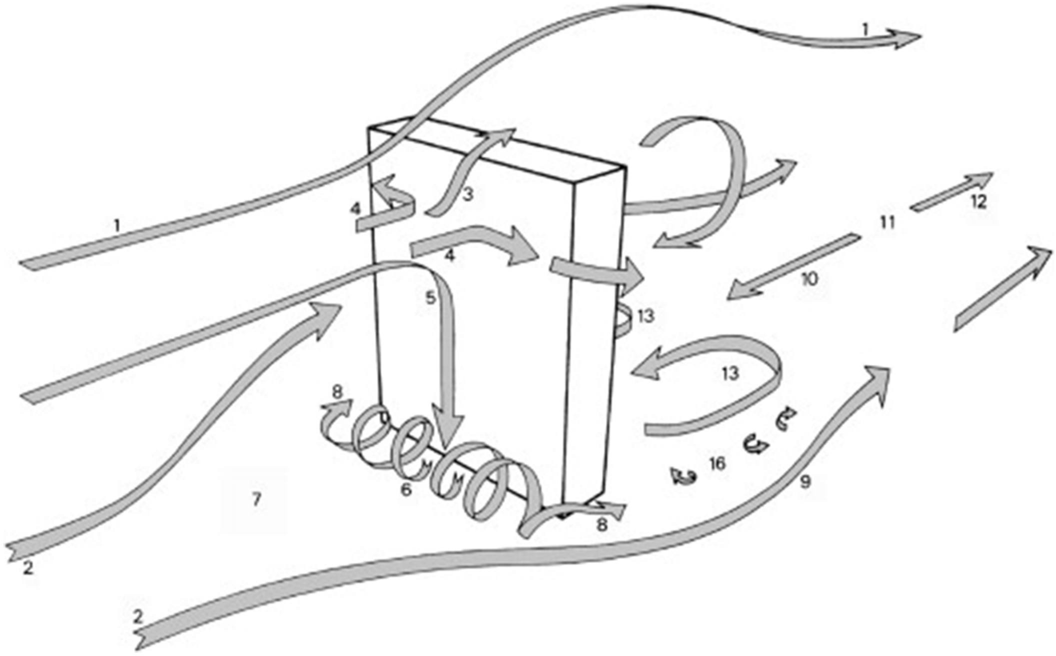

FIGURE 2
Schematic representation of wind flow pattern around a high-rise building (Beranek and Van Koten, 1979). https://creativecommons.org/licenses/by-nc-nd/4.0/

interdisciplinary work demands that participants familiarize themselves with the "language" and methodologies of other disciplines to foster effective communication and collaboration toward achieving common goals (Yigitcanlar, 2015).

In the next points, variables that may affect the implementation and acceptance of this technology by citizens are discussed, concerning the opportunities and limitations that can be found in cities.

2.2 SWTs and other energy technologies in sustainable cities

Urban renewable energy has made notable strides, particularly in the realms of solar photovoltaic (PV) and wind energy. In 2023, approximately 5% of Spanish homes utilized photovoltaic panels (INE, 2024), reflecting the growing adoption of solar technology in urban settings. Solar panels are often preferred due to their efficiency (Etukudoh et al., 2024) and relatively lower visual impact compared to wind turbines, and visual considerations play a crucial role in consumer preferences for residential installations (Bao et al., 2017). However, they come with significant challenges, including substantial space requirements (Etukudoh et al., 2024), high upfront installation costs (Khan et al., 2021), and concerns regarding waste disposal and environmental implications at the end of their lifecycle (Shrestha and Zaman, 2024; Tasnim et al., 2022).

In contrast, wind energy presents advantages such as continuous operational capability (Etukudoh et al., 2024), functioning effectively around the clock, and generally lower initial costs compared to solar installations. This makes wind energy a potentially more consistent and accessible source of renewable energy for urban environments and their inhabitants (Khan et al., 2021). Nonetheless, both solar and wind technologies encounter challenges related to waste management and sustainability. While recycling solar panels is technologically feasible, it remains economically challenging, complicating the transition to a circular economy in solar energy (Kim and Park, 2018). On the other hand, wind turbines exhibit a minimal water footprint, utilizing only 4 milliliters of water per kilowatt-hour (kWh) generated (Table 1), which underscores their comparatively lower environmental impact (Abraham et al., 2012).

In conclusion, while solar PV energy has been adopted in urban areas to a greater extent, wind energy presents unique advantages that position it as a valuable component of sustainable urban energy systems. Its capacity to generate power continuously coupled with relatively lower upfront costs renders it an appealing option for diverse urban settings. Moreover, wind turbines exhibit minimal environmental impact underscoring their sustainability advantages. However, to fully realize the potential of wind energy in urban areas, it is imperative to address challenges such as optimizing turbine designs for complex urban wind patterns and enhancing public acceptance. By prioritizing innovation and integrating wind energy into urban planning, cities can effectively harness its benefits to complement other renewable energy sources, thereby achieving more resilient and sustainable energy systems.

2.3 SWTs impact factors in citizens

Urban wind energy technologies have been developing for years, but due to different factors they have not reached as high success as predicted (Liu et al., 2020; Ishugah et al., 2014). Most investigations address visual impact, noise emitted by the blades or motors, vibrations that can be transmitted through building structures, effects on biodiversity, or even public safety in case of breakages or accidents, especially in SWTs mounted at great heights (Tasneem et al., 2020; Toja-Silva et al., 2013). These approaches are primarily technical but always related to living beings, especially people, who are the inhabitants of the urban areas where this technology seeks to be incorporated.

Improving urban wind energy from a citizen's perspective necessitates the design of wind turbines that are not only acceptable but also beneficial to residents, ensuring that they integrate harmoniously into the urban landscape. The role of industrial design is pivotal in this context as it encompasses the creation of products and systems that align with the needs and preferences of end users. This alignment is essential for enhancing citizen acceptance of urban wind energy, optimizing wind energy efficiency, and reducing associated costs (Bao et al., 2017).

The primary objective of industrial design in the integration of renewable energy sources within urban environments is to develop products and systems that are tailored to the specific requirements of urban infrastructure. This approach requires consideration of all stakeholders involved in the urban ecosystem, including residents, policymakers, and urban planners (Etukudoh et al., 2024). To achieve this, it is crucial to incorporate diverse perspectives throughout the design process, ensuring that the needs of all urban agents are addressed effectively. Several industrial design strategies can be employed to enhance the acceptance of urban wind energy and maximize its benefits for citizens. Moreover, these strategies may vary based on the focus and expertise of different design disciplines (Khan et al., 2021). Each of these approaches is grounded in the understanding of human needs and aspirations, emphasizing the importance of user-centered design in fostering acceptance and engagement with renewable energy technologies.

Sustainability requires creative power. Creativity is increasingly recognized as a fundamental driver of sustainability. For instance, Burns et al. (2016) argue that creativity and innovation are essential for adaptation and sustainability, highlighting the universal nature of these human activities in both evolutionary contexts and everyday life (Burns et al., 2016). It is imperative to position humans and citizens at the center of these new technologies. The integration of human-centric design principles is essential for fostering sustainable urban environments that are not only functional but also resonate with the needs and aspirations of the communities they serve. This approach aligns with the foundational ideas of design science articulated by Fuller (1982), who emphasized the importance of creating solutions that enhance human wellbeing while respecting ecological boundaries. Fuller's vision of "Comprehensive Anticipatory Design Science" advocates for a holistic understanding of design that prioritizes human needs and experiences in the development of sustainable solutions.

The strategic design frameworks proposed by Manzini and Vezzoli further reinforce the necessity of placing citizens at the core of sustainability efforts (Manzini and Vezzoli, 2003). Their work highlights the role of design in facilitating social innovation and empowering communities to actively participate in the creation of sustainable outcomes. By engaging citizens in the design process, urban planners and designers can harness local knowledge and insights, leading to solutions that are more relevant and effective in addressing the unique challenges faced by different communities (Gaventa and Barrett, 2012). This participatory approach not only enhances the quality of urban design but also fosters a sense of ownership and agency among citizens, which is crucial for the long-term success of sustainability initiatives.

Meroni's contributions to the discourse on sustainable design underscore the importance of human-centered approaches in creating meaningful and impactful solutions (Meroni, 2006). By focusing on the interactions between people, products, and services, Meroni advocates for design practices that prioritize user experiences and social wellbeing. This perspective is vital for ensuring that future cities are not merely technological constructs but vibrant, livable spaces that promote social cohesion and community engagement.

Moreover, the collaborative design methods proposed by Bach and Dubois exemplify how interdisciplinary teams can effectively engage citizens in the design process (Emmanuel et al., 2007). By incorporating diverse perspectives and expertise, these methods facilitate the co-creation of urban solutions that reflect the values and aspirations of the community. This collaborative approach is essential for addressing the complexities of urban design as it allows for the exploration of innovative solutions that are grounded in the lived experiences of citizens. For instance, participatory design involves engaging citizens in the design process, allowing them to express their concerns and preferences regarding wind energy installations (Collins and Anctil, 2017). This collaborative approach can lead to more acceptable and contextually relevant designs. Similarly, sustainable design principles can guide the development of wind turbines that minimize environmental impact while maximizing aesthetic appeal and functionality (Shrestha and Zaman, 2024). By focusing on the real needs of individuals and communities, industrial design can significantly contribute to the successful integration of urban wind energy systems.

Contemporary approaches to inclusive design further enrich this discourse. Recent work by Teja and Mani (2022) proposes a framework for human-centered renewable energy transition that explicitly addresses social equity concerns. Their research demonstrates how participatory approaches can identify and address barriers that might otherwise prevent marginalized communities from benefiting from renewable technologies. Similarly, Lennon and Dunphy (2023) highlight the importance of co-designed energy solutions, documenting how community participation throughout the design process leads to higher adoption rates and more equitable outcomes in diverse urban settings.

In conclusion, the integration of human and citizen-centered approaches in the discourse on sustainability and urban design is essential for creating resilient and vibrant future cities. By prioritizing the needs and experiences of individuals and communities, designers can develop innovative solutions that not only address environmental challenges but also enhance social wellbeing and foster a sense of belonging. The collective works of Fuller, Manzini, Vezzoli, Meroni, Bach, Dubois, and contemporary researchers underscore the importance of placing humans at the heart of sustainable design practices, paving the way for a more inclusive and sustainable urban future.

Regarding the resilience of cities toward people and sustainability, it is important to understand why consumers want to participate in the energy transition process. Questions such as how communities can be involved in the sustainable development of their buildings are becoming more common among citizens.

TABLE 1 Water consumption of some energy technologies, per kWh generated (Saidur et al., 2011).

Technology	Litters/KWh
Nuclear	2.30
Coal	1.90
Oil	1.60
Combined cycle gas	0.95
Wind	0.004
Solar	0.110

> *"For global energy to be 100% renewable, today's actions must be worked out as a bottom-up process. It is necessary to empower citizens and communities around the world to become drivers of great transformation. People realizing the benefits of using national renewable resources will be an unstoppable force for a more just, peaceful, and climate-friendly world."* Stefan Gsänger, WWEA (World Wind Energy Association, 2023).

According to the European Commission, "As the fight against climate change increasingly involves solutions at all levels and the involvement of citizens, cities are well placed to show leadership in the transition to clean energy" (European Commission, 2022).

The transition to sustainability may require different criteria and orientations for strategic design than those previously used, i.e., strategic design to orient companies beyond their markets, current production and delivery processes, or industrial consortia in their areas (Keinonen and Takala, 2010). Although traditional types of strategic design are situated within sustainable design, transitions to sustainability also show the potential for new types of strategic design, where the pure benefactor, and therefore the organization that defines strategic goals and makes strategic decisions, is not self-interested. A 2017 project on integrating social consequences in Denmark proved that it is crucial to take into account human variables such as social aspects and impacts, local benefits, uncertainty, fears and hopes of citizens, user-friendly communication, and more basic issues such as private property and its invasion in renewable energy projects (Larsen et al., 2017).

Earlier key studies highlight "social acceptance" of wind energy in countries such as France and Germany (Jobert et al., 2007) which speak about creating trust between developers and local actors, ownership, information and participation, influence on local economy and tourism, or geographic impact, all of them related to citizens.

The implementation of wind energy faces challenges, including noise pollution and its impact on community wellbeing (Shepherd and Billington, 2011). The successful adoption of wind energy requires a socialization process, embedding the technology within society (Heidenreich, 2014). This process involves various stakeholders, from inventors and entrepreneurs to policymakers and local communities (Asmus, 2000; Krauss, 2010). The development of wind energy is not just a top-down approach but a collective effort involving human and non-human factors (Krauss, 2010). Individuals develop skills to manage wind flow in their daily lives, highlighting the complex relationship between humans and energy (Senior, 2016).

In addition, it is important for the final user, the citizen, to perceive the technology as a socio-economically accessible option. In their yearly dossier, European Anti-Poverty Network (EAPN) repeatedly showcases that new technologies are not reachable for a considerable number of homes in Europe. The 2020 Energy Poverty report (EAPN, 2020) indicates that 8.2% of households in Europe cannot afford to maintain good living conditions in their homes but also points to the decarbonization of the heating and cooling sector in all residential buildings to avoid energy poor households paying the carbon price in the energy transition in the coming decades. For an equitable and just ecological transition, it is important to be able to offer accessible and inclusive means of energy generation.

To address energy poverty concerns, several approaches can make SWTs more accessible:

1. Modular and scalable designs that allow users to start with smaller, affordable units and expand capacity incrementally.
2. Community ownership models where multiple households share investment costs and benefits.
3. Targeted subsidy programs based on income thresholds, similar to existing solar incentive structures.
4. Pay-as-you-save financing mechanisms where initial costs are covered by a third party and repaid through energy savings.
5. Simplified maintenance requirements and open-source repair documentation to reduce long-term costs.

In such a case, design can provide a proactive concept and visualization of options in the presence of multiple competing values to consider. For this, we can refer to the value-sensitive design (VSD) framework (Mok and Hyysalo, 2018). Although in its origins it is linked to computer and information systems, VSD is a continually evolving methodology that is, for some, the greatest approximation to the real consideration of human values in technology design (e.g., Davis and Nathan, 2015). VSD incorporates ethically relevant values such as environmental sustainability in design work beyond instrumental goods or economic value (Friedman et al., 2013).

Value-sensitive design (VSD) provides a particularly relevant framework for SWTs as it explicitly addresses competing values in technical implementations. In urban wind energy installations, VSD's iterative approach can balance energy generation efficiency (technical value) with community aesthetics, noise considerations, and accessibility (human values). Applying VSD principles to SWT design involves identifying stakeholder values through participatory research, translating these values into design requirements (e.g., maximum acceptable noise levels and visual integration parameters), prototyping solutions, and evaluating with community members.

Similarly, assemblage thinking offers a conceptual framework for understanding how SWTs function within complex urban networks. Rather than viewing turbines as isolated technical objects, this approach recognizes them as elements within socio-technical assemblages that include buildings, energy systems, residents, regulations, and urban spaces. This perspective is especially valuable for SWT integration because it allows designers to identify potential friction points and synergies within existing urban assemblages.

In a type of governance which takes forward the progress of systems transition (Verbong and Loorbach, 2012), design approaches (e.g., VSD) can help clarify concerns and provide alternative solutions to the debate among stakeholders (who may have opposed interests from the start) and end users. Sustainable design initiatives must consider how they relate to wider sustainability transitions and choose their modes of participation to enhance their relevance and potential

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for change. Visualizations and documentation of successful demonstration projects can provide precision for guidelines and statutes and in this case for guidelines on the siting of renewable energy in heritage buildings (currently written from a categoric: "wind energy is always an aesthetic violation").

2.4 Insights from state-of-the-art analysis

This state of the art, which cross-referenced information on cities and small wind turbines (SWTs), concludes that to achieve a just and inclusive energy transition, it is important to consider the diverse actors within the urban ecosystem. We must reduce the energy dependency that has been so evident in recent crises, thereby achieving energy security, which in turn will promote equity and sustainability in a broader sense.

First of all, we must differentiate between the nature of these actors involved in the system, if we look at it as a whole. We can differentiate between groups according to decision-making power, economic interest, or personal interest as human wellbeing, among others (Figure 3). The nature of this study is a concern about the lack of consideration of some of these actors in incorporating industrial products such as small wind power into the daily lives of people living in urban environments. We focus on it from the beginning.

Promoting local energy generation requires including all people residing in the area and incorporating their concerns and needs into the process of creating these industrial machines, such as renewable energy technologies tailored for urban environments. SWTs have proven to be, in comparison with other emerging technologies such as photovoltaics, solutions that require less space, have a lower hydrological impact, and have significantly lower product and initial installation costs.

SWT solutions seem to be more democratic for society than other energy technologies, if we use democratic adjective as Oxford "favoring or characterized by social equality" definition and referring to how energy self-sufficient citizens are. Some currents of democratizing product democratization, from an IoT point of view, more digital and through wearables and apps, work on communication and making technologies more understandable and accessible, in terms of skills (López-de-Ipiña et al., 2024), influencing from a second row in sustainable urban planning processes and policymaking.

However, SWTs also generate mistrust and doubts about their visual impact, possible noise and vibrations, or safety for people living in the environment and for urban biodiversity. These weaknesses mentioned, if we analyze them as a group of gaps, are clearly a response of those people who will have to deal with these industrial machines on a daily basis, the citizens, not of those agents who make the decision to implement them into their residential buildings.

The lack of interdisciplinarity may be another contributing factor, both in academia and the failure to not co-create with the actors who stand to benefit from this energy, the citizens. To create livable cities of the future, Fuller emphasizes the importance of working toward human wellbeing, by centering sustainable transformation on citizens and communities. Approaches such as comprehensive anticipatory design science can help visualize a desired future state to work toward. This involves empowering communities, making people active

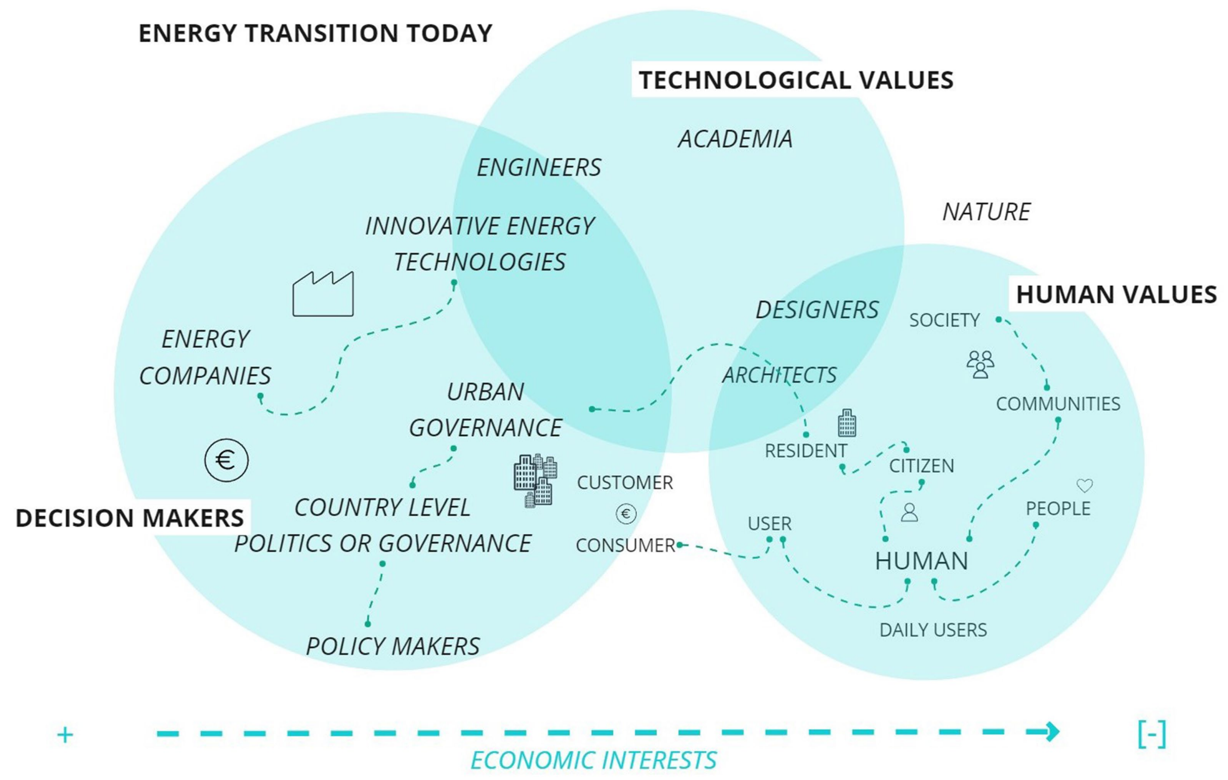

FIGURE 3
Current state of energy transition, showing the separation between decision-making power, economic interest, and personal wellbeing.

participants in change, respecting local knowledge and lifeways, and thus contributing to social innovation grounded in a sense of belonging, as Manzini and Vezzoli have taught us. Bach and Dubois highlight the significance of involving communities in the development of sustainable and livable buildings.

Similarly, it is crucial to consider the cultural and architectural environment of cities at a local level. The majority of scientific articles related to urban wind energy treat buildings as isolated entities, focusing on inserting or adding artifacts in different locations or positions, without accounting for their potential cultural impact. As cited in value-sensitive design (VSD) practices, human values must be weighed against technological values to achieve an ethical solution through an iterative process.

The following diagram (Figure 4) shows our proposal for a more integrated approach to energy transition, centering human values in technological development. This shifts the focus to the inhabitants of cities and redistributes decision-making power to create a more equitable system.

3 Analyzing current research: semi-systematic review

This section describes a semi-systematic review conducted to provide an overview of the existing research on the relationship between SWTs and the human insights identified in the previous section. In contrast to systematic reviews, which aim to quantitatively answer specific research questions or hypotheses by identifying and analyzing all available empirical evidence, a semi-systematic review adopts a broader research approach (Snyder, 2019). The semi-systematic review process involved examining research areas and tracking their evolution over time and synthesizing the main themes,

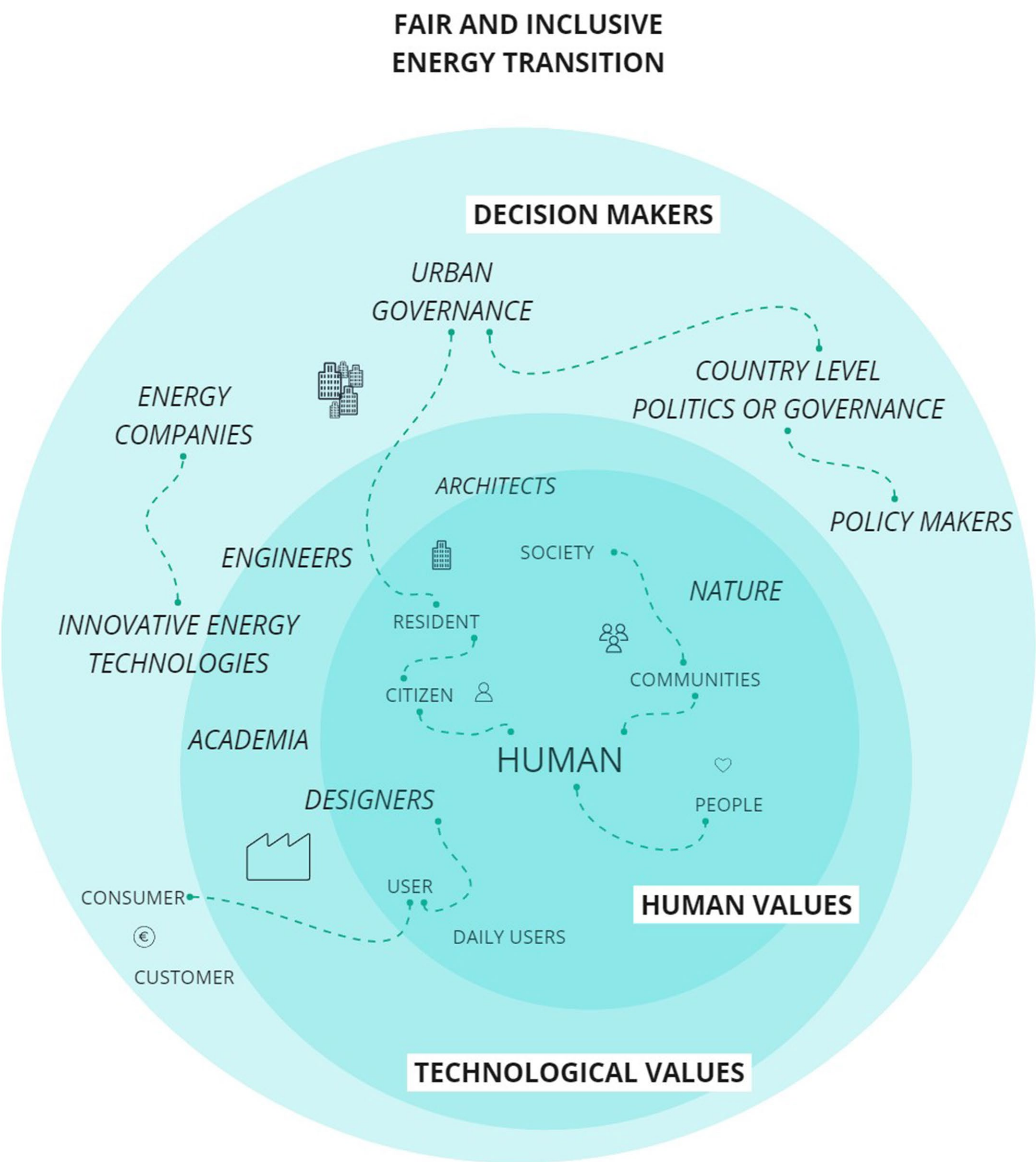

FIGURE 4
Proposed framework for a fair and inclusive energy transition that unifies decision-making power, economic interests, and personal wellbeing.

theoretical perspectives, and other qualitative information related to the topic, using meta-narratives instead of quantitative methods. This approach has been particularly useful for the current research subject as it allows for a comprehensive understanding of how the topic has developed across different research traditions.

The resulting themes from the semi-systematic review enabled the collection of insights and limitations from the literature. These insights will guide the subsequent review of technological solutions and inform the opportunities for future research and design, as discussed in the Conclusion section.

3.1 Methodology

Our semi-systematic review followed a rigorous five-stage process: (1) search strategy development, (2) identification and screening, (3) eligibility assessment, (4) data extraction and analysis, and (5) synthesis and interpretation.

We developed a precise search string based on preliminary scoping reviews: (TITLE-ABS-KEY ("urban wind energy" OR "urban wind turbines" OR "small wind turbines") AND ALL ("human*")). The search was conducted in SCOPUS, limited to peer-reviewed English-language journal articles published between 2004 and 2024.

Scopus database was selected due to its broad multidisciplinary coverage and its relevance in the fields of Industrial Design and Engineering. In addition, its indexing of peer-reviewed journals and advanced filtering and analysis tools ensure the quality, rigor, and reproducibility of the search.

The study conducts a comprehensive review of existing literature on urban wind energy, focusing on the current state of SWT technologies and their challenges in cities and related to citizens, as we have seen in previous points. This includes extracting insights for examining various research articles related to turbine design, efficiency, and urban integration using a semi-systematic review, to extract different ways and theoretical perspectives related to humans into them (Figure 5).

First of all, to filter the relevant articles related to the variables detected in the theoretical framework, the following search string was used in academic literature search engine SCOPUS: (TITLE-ABS-KEY ("urban wind energy" OR "urban wind turbines" OR "small wind turbines") AND ALL ("variable*")). For a first snapshot of the situation, as defined as human values on insight extraction from the literature (Figure 4), several variables were checked as identification tests (Figure 6).

This first approximation to the results has been useful as a comparison, on the basis that the number of scientific articles in the last 20 years relating to (TITLE-ABS-KEY ("urban wind energy" OR "urban wind turbines" OR "small wind turbines")) is considerably greater ($n = 2{,}160$), than the one that has obtained the most results in relation to any human variable (society, e.g., $n = 752$). And if, according to the above considerations, we take as a reference point the individuality of the person, as far as possible to economic interests as the customer could be, we can affirm that this difference is more than significant (citizen, e.g., $n = 4$).

To narrow down the analysis, it was decided to carry out the filtering with the common variable 'human' and then to mention the presence of the other variables in these documents in the final data extraction and synthesis. Using (TITLE-ABS-KEY ("urban wind energy" OR "urban wind turbines" OR "small wind turbines") AND ALL ("human*")) search string in SCOPUS, with a filter for the last 20 years (2004–2024), 111 articles were identified. Initial screening excluded non-English texts ($n = 2$), non-journal articles ($n = 44$), and inaccessible full texts ($n = 2$). The remaining 63 articles underwent full-text screening against predetermined inclusion criteria: (a) primary focus on urban wind energy applications, (b) explicit consideration of human factors, and (c) relevance to design integration. This resulted in 27 articles for final analysis (Figure 7).

This study adopted a qualitative data analysis approach to examine the theoretical perspective of the articles under investigation. The method employed the following steps:

1 Coding—Thematic coding of key sections in the selected texts.
2 Categorization—Grouping codes into broader conceptual categories.
3 Theme Identification—Identifying overarching themes across the studies.
4 Interpretation—Extracting key insights from the literature and synthesizing findings.
5 Limitations—Identifying constraints in the reviewed research and methodological considerations.

The ATLAS.ti Web software was utilized to facilitate the coding, categorization, and theme identification stages of this in-depth qualitative analysis. ATLAS.ti Web is not a generative AI tool but rather specialized qualitative data analysis software designed for systematic coding and analysis of textual data.

By following this methodology, the study provides a comprehensive synthesis of research on urban wind energy while incorporating a human-centered perspective, offering valuable insights into design and implementation challenges in urban environments.

3.2 Results

These methods collectively aim to identify success factors, challenges, and opportunities for improving the acceptance and effectiveness of SWTs in urban areas, directly related to their inhabitants and the democratization of urban technologies.

To categorize the different points of view, theoretical perspectives, and how the human factor has been taken into account in these 27 publications, labels have been created that have been categorized at various levels (Figure 8).

In order to be able to carry out this labeling, all the forms in which human beings can be present in the texts have been identified apart from the word 'human'. For this purpose, all keywords related to human values (Figure 4) were searched for, based on the previous bibliographic review: people, citizen, resident, community, user, customer (consumer), wildlife (fauna, flora), society (social), and participative and democratic (democracy).

After all text reading and labeling, a first label connection diagram has been made (Figure 9) to have a conceptual map of the main concerns and purposes, interests, and contributions on urban wind energy of the scientific world today (2004–2024). The authors of the articles have been placed in the center of diagram, from least to most recent, and with regard to the use of the human

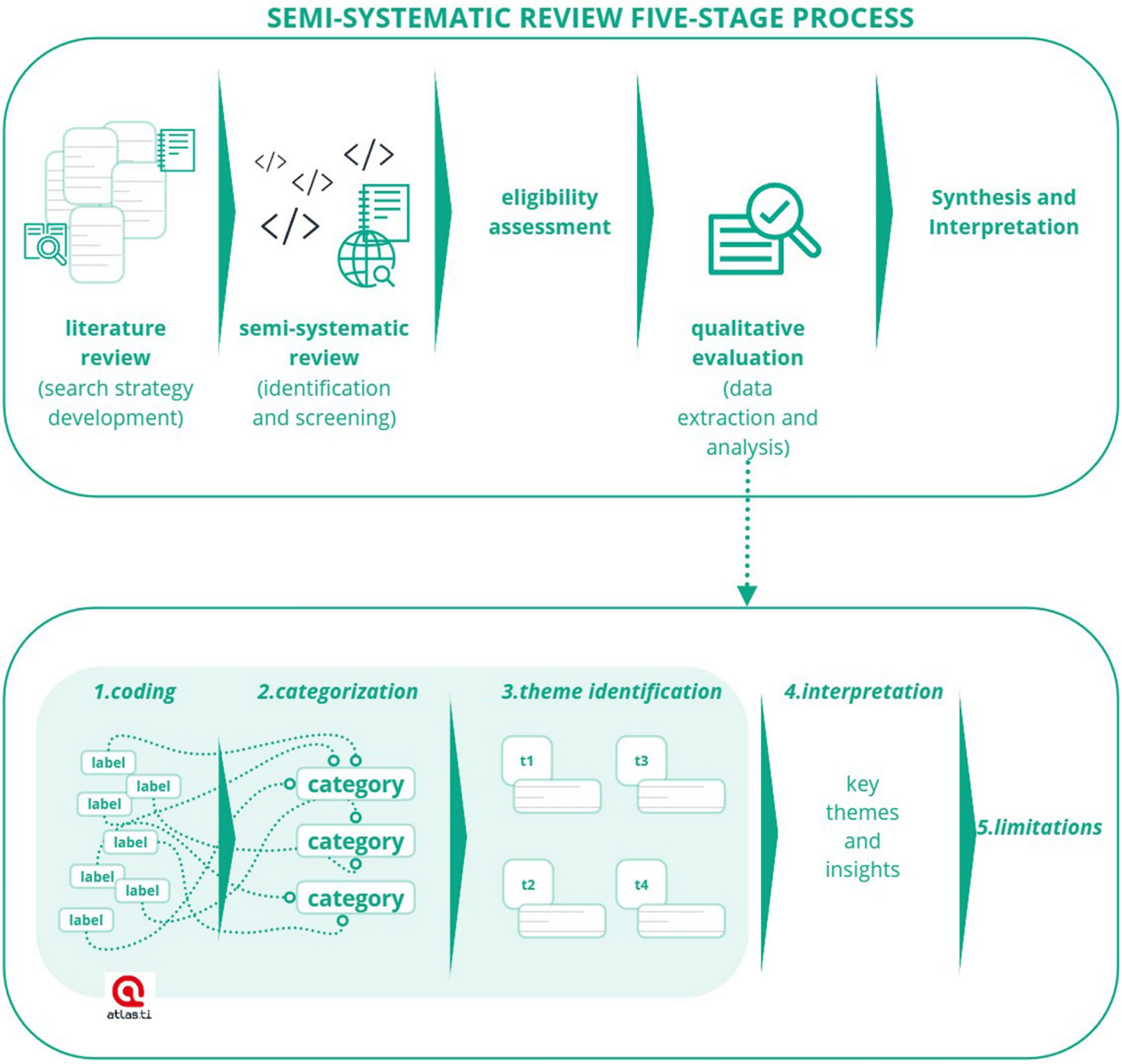

FIGURE 5
Diagram of the methodology used for data extraction.

being in their contributions, the role of the 'human' has been indicated in terms of how involved it is (in the seven levels mentioned), and in what way it has been incorporated in each research (context, qualitative research, or quantitative process). In this categorization, articles in which user research has been carried out have been marked in a different color (blue). In the right-hand column, each author and his or her way of doing things has been related to the main purpose of each written communication.

3.2.1 Main topic

The main research focus of each article has been labeled (Figure 9). In this way, it has been possible to categorize them in different groups: (a) use of SWT at product level, (b) development of new forms of blades, (c) noise generated by turbines, (d) analysis of efficiency improvement, and (e) other additional applications.

Those whose main contribution speaks about SWT as a final product (37% of research) are based on this energy production such as a finished product or technology. Concerns include how to incorporate it in its use environment, and how they could redesign it to address the problems that have emerged in the last phase of implementation. Noise is one of these widespread causes of human rejection and occupies around a quarter of the research, in which we can also incorporate the amount of research focused on improving rotor blades. Development of new forms of blades based on different secondary reasons such as noise and efficiency. The analysis of efficiency improvements is around the finished product and its implementation in different environments, very tentatively taking into account the inhabitants, and the other approaches on, e.g., IoT, wind cleaning or urban planning, which move away from our focus on urban wind power generation solutions have been categorized as other additions or applications.

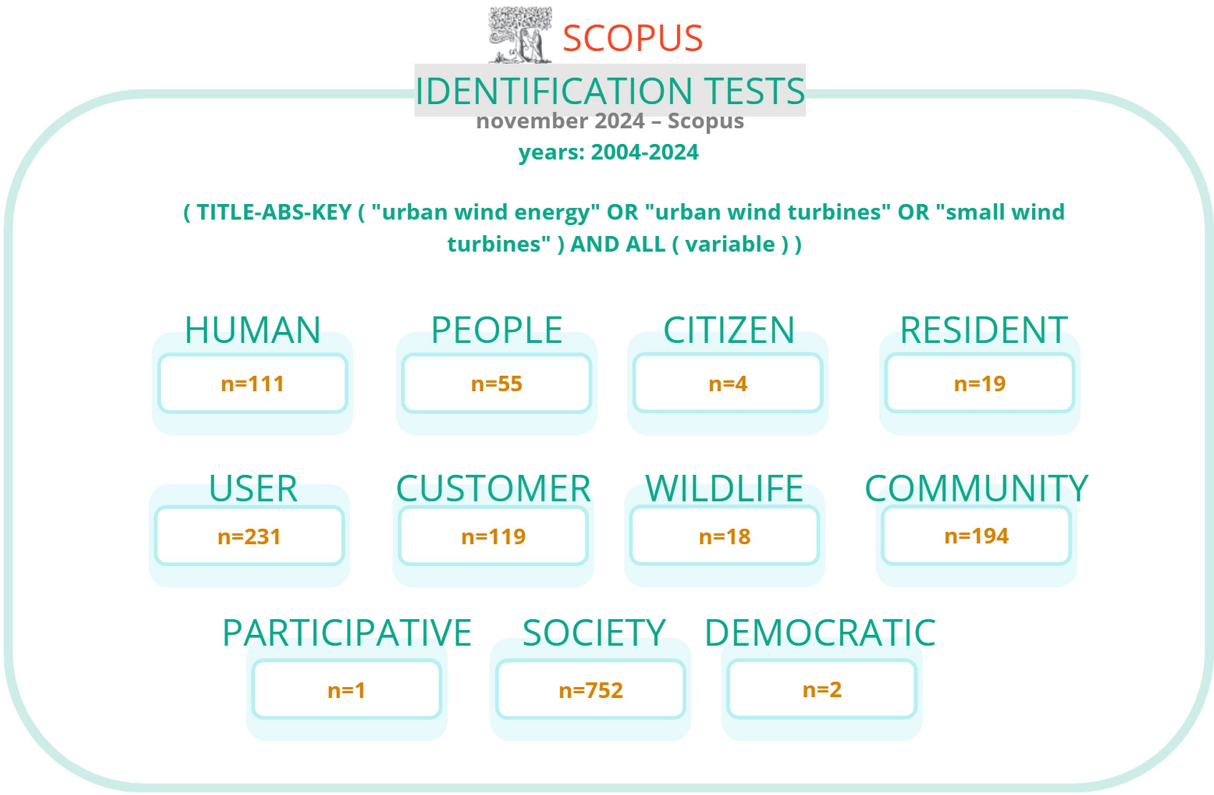

FIGURE 6
First snapshot of the situation, human value-related variables from insight extraction in contextualization literature review.

3.2.2 Knowledge areas

In addition, a distinction has also been made on the basis of the area of knowledge of each publication (Figure 10). It has been considered important to contrast the areas of knowledge of the journals in which these publications have been published with the actual area of knowledge of the authors making the scientific contribution. The authors are those who create knowledge, and the journal is in charge of opening this contribution to the world, where the majority of the public will depend on their area of knowledge.

The area of engineering is predominant, 70%, among the authors in this case. Most of the contributions on urban wind energy in which human beings are taken into account are from the technological perspective of engineering. Even if we delve into the interdisciplinarity found, half of them are led by engineers, collaborating with areas such as environmental science or energy, and are always aimed at journals in areas other than engineering. On the other hand, we observe that these contributions from engineering diversify into many areas of knowledge and not always to more affine technical areas of technology. We can conclude that engineering has been the area of knowledge that has most incorporated the human factor in its contributions to wind energy in cities.

3.2.3 Human involvement in research

On the other hand, it has been analyzed at what level the human is involved in each text, creating six levels ranging from the mere mention of human as a population of interest, most of the time mentioned only as part of the contextualization, to the involvement of the human being as an agent of decision-making. Specifically focusing on the latter cases where humans take a more important role, a deeper analysis has been made (Table 2). A comprehensive understanding and prioritization of these stakeholder roles are essential for fostering inclusive, balanced, and effective co-creation processes that meet shared objectives. Primary stakeholders, or core contributors, are individuals or groups such as end users, customers, designers, and key partners whose direct engagement is vital for the success of co-creation, as their insights and feedback significantly shape outcomes (Sanders and Stappers, 2008). Secondary stakeholders, referred to as influencers, include suppliers, policymakers, and community leaders, who, while not actively involved in every step, exert a moderate-to-high influence by providing essential resources, expertise, or regulatory context. Tertiary stakeholders, or supportive/peripheral players, have minimal involvement but can offer valuable context-specific knowledge, thus holding a low to moderate importance. Overarching stakeholders, or strategic overseers, such as executives, investors, and regulatory bodies, focus on ensuring that co-creation aligns with broader organizational or societal goals, wielding high importance as their decisions can either facilitate or hinder the process (Arnstein, 1969). Factors influencing stakeholder importance include their level of expertise, degree of influence, alignment of stakeholder needs with outcomes, and their potential for engagement. This study is valuing human levels of involvement in processes, as individuals, so it has been taken into account only

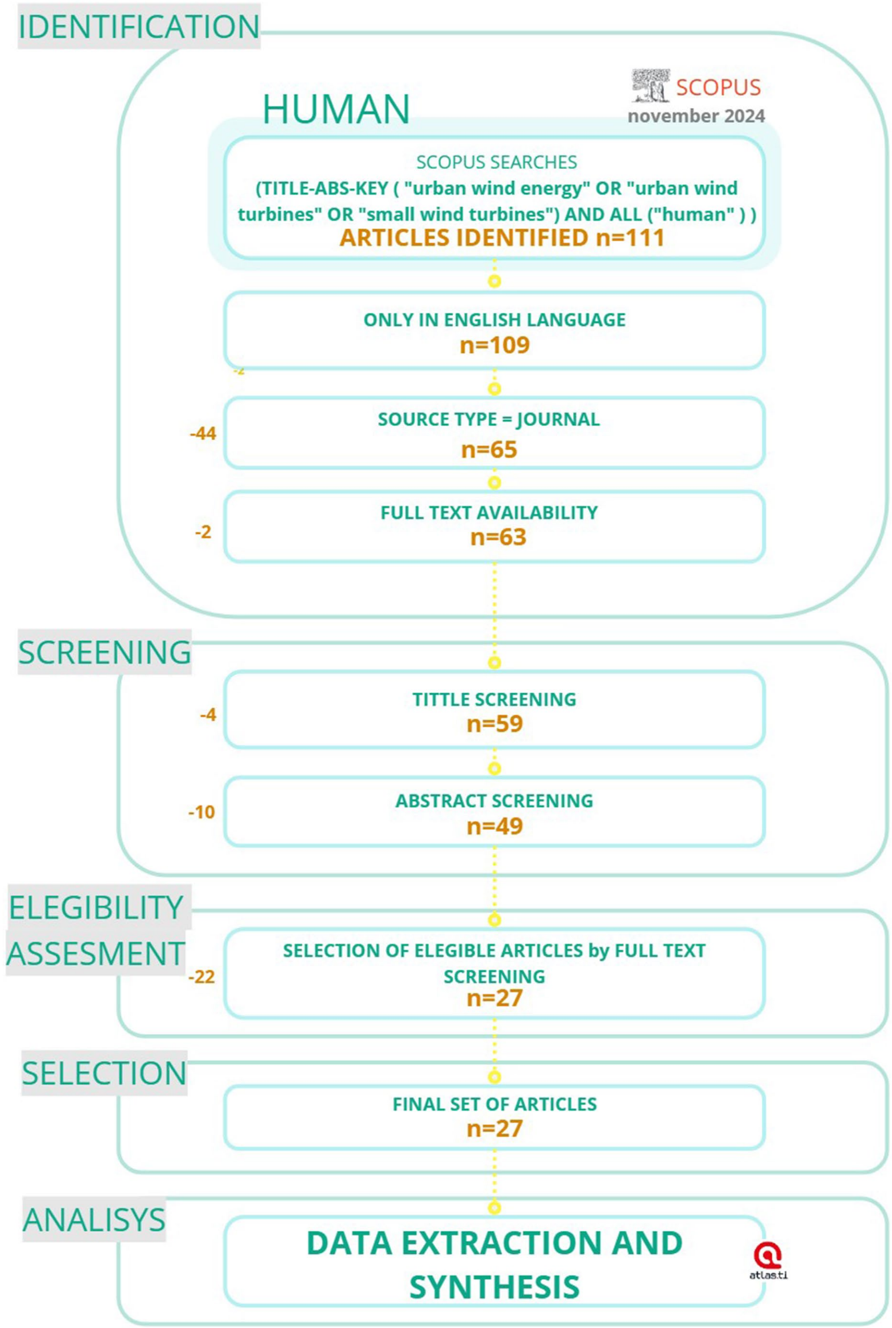

FIGURE 7
Diagram of the research process for our semi-systematic literature review. Source: own elaboration, based on PRISMA flow diagram, adapted from Page et al. (2021).

primary and secondary levels, to add them as the most participative involvements of this research. The six levels created for labeling are Population of Interest, Power Generators, Consumer, Important Actor (as someone to take into account), Part of Solution (as influencers of final product aspects), and finally Decision-Maker (as core contributors creating the product).

Approximately 40% of the articles use humans as passive subjects of study, and half of these only use it referring to the population of interest, but there are other 60% of authors involving humans in their process and research that can be seen in Table 2. It has been analyzed how the papers labeled as "Part of the Solution" and "Decision-Maker" involve inhabitants actively in their processes and research. Moreover, among the papers that involve people as "Important Actors," only those that understand that people should be involved from the beginning, before problems come to light, and not afterward, have been considered, incorporating the concerns and needs of humans in the very creation of the products. This perspective is one that denotes an understanding of the individual as part of cities or buildings (Lunevich and Kloppenburg, 2023), and at least one that stakeholders should keep an eye on (Vallejo Díaz et al., 2024).

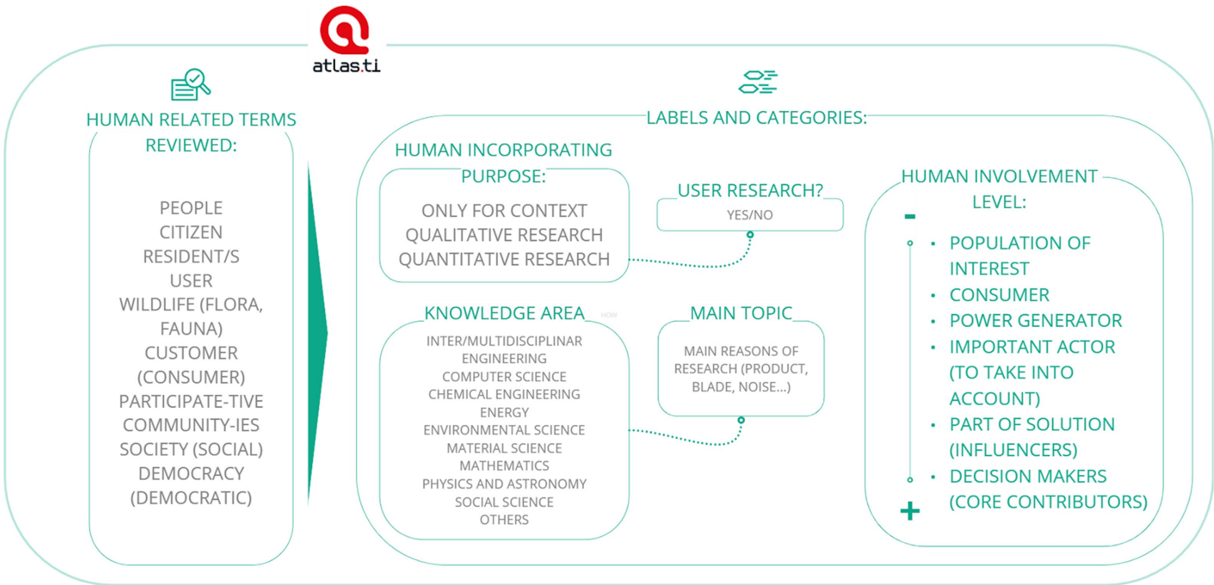

FIGURE 8
Data extraction and synthesis process scheme, carried out in ATLAS.ti Web.

3.2.4 User involvement strategies

Regarding user involvement strategies, this section deepens into the strategies that papers categorized in "Part of the solution" and "Decision-maker" have followed for their work. Table 2 showcases a summary of those strategies and the specific user research tools they have applied. These methodologies are crucial for understanding the needs and experiences of end users, particularly in the context of new technologies.

3.2.5 Human incorporating purpose

Finally, it has been analyzed, in a categorical way, how and when the human being is considered. This categorization is closely linked to previous ones, but in this case, it has been labeled, if it is present, use of human concept only for Context, or whether people have been involved in the deeper research, differentiating its presence between a qualitative or quantitative way.

According to the number of authors using human-related concepts only as population of interest or consumers, self-interest use, almost half of the articles make use of this only to contextualize the subject matter. Of the other half, most make basic human qualitative use based on information from other authors or articles, beyond the minority that dares to incorporate people directly affected into the process itself, as an important part of the process (Table 2).

4 Discussion

The growing need to adopt renewable energy sources in urban environments is a topic of vital importance today. This discussion explores the critical factors influencing the adoption and success of SWT in cities, highlighting the role of human-centered design, interdisciplinary collaboration, and strategic planning in overcoming barriers and maximizing benefits.

Thus, to ensure a successful transition, the following elements should be prioritized:

- Active community engagement, participatory design, and demonstration projects: Foster trust and participation by involving citizens in the design, implementation, and decision-making processes for renewable energy projects. Showcase successful case studies and involve stakeholders in co-creating solutions to enhance acceptance and functionality. When considering the different levels of human involvement, it becomes evident that studies integrating citizens as co-creators in the design process, as decision-makers, tend to address these factors more effectively. By involving communities in decision-making and the design of SWTs, it is possible to identify and prioritize the features that are most valued by end users, which in turn can increase acceptance and success of these technologies. Moreover, the inclusion of human perspectives in design can foster a sense of ownership and responsibility among citizens, which is fundamental for the sustainability of energy solutions. This participatory approach not only enhances the quality of the design but also contributes to a more equitable energy transition, where the concerns and needs of citizens are heard and addressed (Arnstein, 1969).
- Socio-economic accessibility: equally important is ensuring socio-economic accessibility to avoid creating disparities in the transition to clean energy. Ensure that energy-poor households are not excluded and promote equitable access to renewable energy technologies.
- Comprehensive frameworks: use methodologies such as value-sensitive design (VSD) to address ethical, environmental, and social considerations in renewable energy design. The transition to sustainable urban environments requires a human-centered approach that prioritizes citizens' needs, values, and active participation. Renewable energy technologies, particularly wind energy, hold immense potential but face challenges such as social

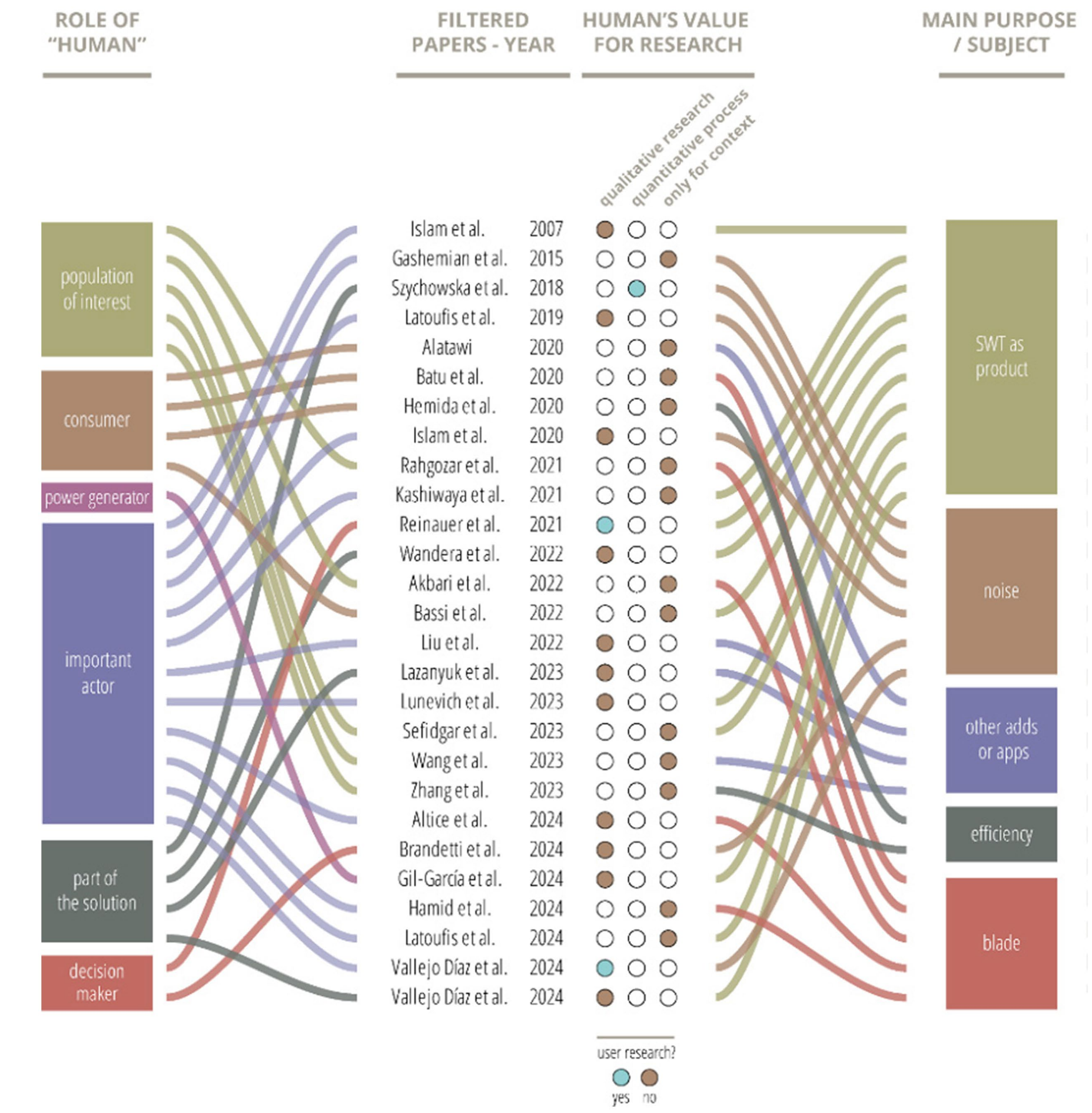

FIGURE 9
Theoretical perspectives that have emerged from qualitative analysis of the literature focusing on the presence of human beings in SWT-related studies, 2004–2024.

acceptance, accessibility, and integration into daily life. Addressing these issues requires collaboration among stakeholders, including policymakers, designers, and local communities.

- Transparency and communication: provide clear, accessible information about the benefits, challenges, and impacts of renewable energy systems to build public trust. A lack of information creates the first barrier that prevents people from trusting the technology that can be offered to them. The importance of engaging communities cannot be overstated, as fostering trust, ensuring transparency, and involving citizens in decision-making processes are crucial for the widespread adoption of technologies such as wind energy. Similarly, communication and interaction between companies and end users must be addressed by training citizens to understand the technical and maintenance issues of urban small wind turbines so that the end user is not afraid to switch to prosumerism (Altice et al., 2024).
- Address local concerns: tackle challenges such as noise pollution, visual impact, and geographic compatibility to improve integration within urban and heritage contexts. The design approaches mentioned in this context include attention to aspects such as urban aesthetics, noise levels, safety, and the democratization of the implementation process. These factors are essential to ensure that SWTs are not only technically viable but

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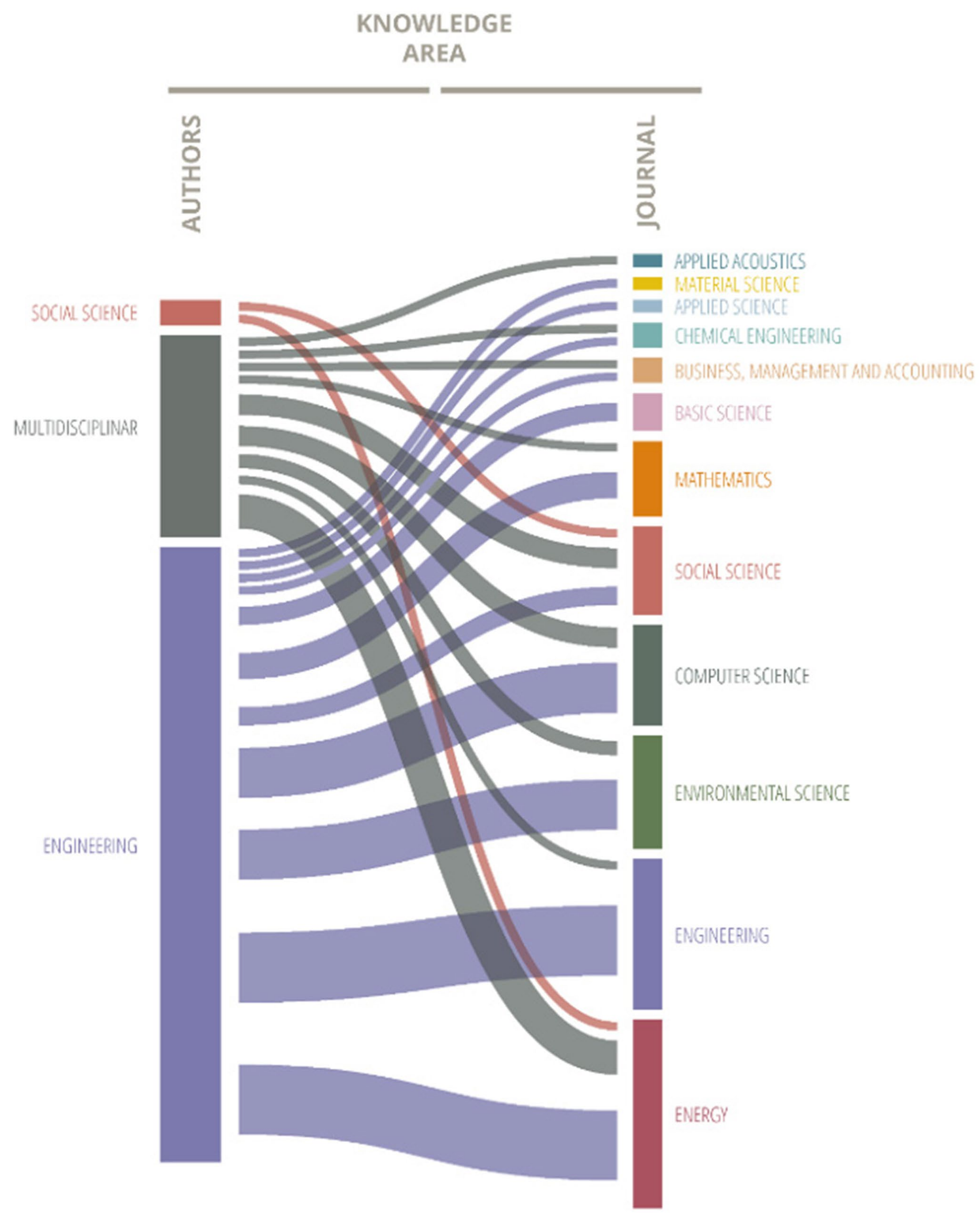

FIGURE 10
Authors knowledge areas contribution to Journal knowledge areas, in SWT development for urban areas with a human perspective, 2004–2024.

also socially acceptable and aligned with citizens' expectations, addressing residents' concerns about the alteration of the urban landscape and their quality of life.

- Sustainability and lifecycle management: ensure renewable energy systems are designed with minimal environmental impact and effective lifecycle processes.
- Policy and regulation support: develop clear guidelines and supportive policies that encourage innovation while protecting citizens' interests and heritage sites.

A more holistic understanding of how energy solutions can be developed that are not only technically innovative but also sensitive to the realities and expectations of urban communities can overcome barriers to adoption and achieve a resilient, equitable, and sustainable urban future that benefits all members of society. This comprehensive approach is essential for moving toward a more sustainable and socially responsible future for energy, and it is fully scalable at the product level when it comes to SWTs.

Design helps to understand and embrace these essential aspects of urban wind power generation solutions, such as energy transition solutions, so it is necessary to focus on tools and perspectives that can help to redirect certain critical aspects.

4.1 Design implications

Human-centric design principles are fundamental to the development of sustainable urban technologies (as SWT) that resonate

TABLE 2 Comparative of strategies and tools used to involve humans in the most prominent articles.

Paper	User involvement level	Description of involvement	Tools
Szychowska et al. (2018)	Part of solution	Participative process with 44 individual users/citizens to understand the problem of noise and find better solutions for human health. Visual impact considered.	User research
Reinauer and Hansen (2021)	Decision-maker	Open-source hardware (OSH) projects; users as decision-makers due to prosumerism. Analyzes user motivations, technical skills, and financial resources.	User research. Transformative social innovation
Wandera et al. (2021)	Part of solution	Highlights communication between customer and company to improve local capabilities for technology maintenance and economic growth. Users in product implementation.	Suppliers survey (indirect individual user info)
Lazanyuk et al. (2023)	Part of solution	Communication between customer and company to transform user values and environmental awareness, achieving prosumerism. One-way communication.	–
Lunevich and Kloppenburg, 2023	Important actor	Buildings as socio-technical networks involving multiple actors (architects, engineers, municipal workers, inhabitants, etc.), not just fixed structures.	Assemblage thinking
Brandetti et al. (2024)	Decision-maker	Focuses on psychoacoustic annoyance and perception of wind turbine noise. Users' noise annoyance should be considered in design and decision-making for VAWTs.	–
Vallejo Díaz et al. (2024)-01	Important actor	Focuses on human health and safety, considering individuals as important but not decision-makers. Other stakeholders hold decision power.	Stakeholder survey (indirect individual user info)
Vallejo Díaz and Herrera Moya (2024)-05	Part of solution	Discusses social/community resilience and cooperation. Highlights gaps in studies on people's psychological patterns for understanding preferences and motivation.	–

with the needs and preferences of urban residents. The concept of human-centered design emphasizes the importance of tailoring solutions to local contexts and community values. This approach aligns with the principles of co-creation, where stakeholders—including residents—actively engage in the design process. Such participatory strategies have been shown to enhance the relevance and acceptance of technological solutions within urban environments, fostering a sense of ownership and agency among citizens (Carlgren et al., 2016; Prahalad and Ramaswamy, 2004; Prinsenberg et al., 2020). By prioritizing user experience, SWT solutions can integrate seamlessly into urban landscapes, thereby enhancing their effectiveness and appeal (Mulder and Magni, 2022).

The vision of "Comprehensive Anticipatory Design Science" as articulated by Fuller underscores the necessity of a holistic understanding of design that prioritizes human needs and experiences. This perspective is echoed in the work of Manzini, who highlights the role of design in facilitating social innovation and empowering communities to participate actively in creating sustainable outcomes (Manzini and Coad, 2015). Their research indicates that when communities are involved in the design process, it not only leads to more effective solutions but also cultivates a sense of agency among participants, which is crucial for the long-term success of social innovations (Hillgren et al., 2011). Furthermore, the integration of interdisciplinary approaches is essential for addressing the complex interplay of technical, social, and environmental factors inherent in urban settings. Frameworks such as value-sensitive design (VSD) provide structured methodologies that balance these competing priorities, ensuring that technological advancements are both ethically and socially informed (Verganti, 2008; Gatzweiler, 2016).

Assemblage thinking (Kamalipour and Peimani, 2015), which emphasizes the interconnectedness of various elements within a system, can also be applied to the development of SWT. This perspective allows for a more nuanced understanding of how different components—technological, social, and environmental—interact within urban contexts. By adopting an interdisciplinary approach that incorporates insights from engineering, design, social sciences, and urban planning, stakeholders can better navigate the complexities of urban integration (Yadav et al., 2022; Goodyear-Smith et al., 2015). The emphasis on co-creation and participative processes not only enhances the relevance of design solutions but also fosters collaborative learning environments that empower urban innovators to drive transformative social change (Mulder and Magni, 2022; Sanders and Stappers, 2008).

Employing transformative social innovation frameworks, such as Vision in Product Design (Tromp and Hekkert, 2016), further emphasizes the creation of adaptive and future-oriented solutions. By addressing these considerations, SWT designs can transcend technical functionality to become symbols of sustainability and urban innovation. By positioning these turbines as symbols of innovation, cities can promote environmental awareness and encourage community participation in renewable energy initiatives (Vanhamäki et al., 2017). This aligns with the transformative social innovation framework, which emphasizes the importance of creating adaptive solutions that resonate with societal values and aspirations (Hépal and Puškár, 2016).

Incorporating sound design principles into urban planning is essential for mitigating noise annoyance, particularly in densely populated areas. Noise annoyance is a significant concern for urban residents as it can adversely affect mental health and overall quality of life. Research has shown that the intensity of sound pressure levels (SPL) and individual perceptions of noise sources play critical roles in determining levels of annoyance (Botelho et al., 2017; Madvari et al., 2022). For instance, studies indicate that negative attitudes toward specific noise sources, such as wind turbines, can exacerbate feelings of annoyance, suggesting that sound design should not only focus on reducing SPL but also on addressing public perceptions and attitudes toward these sources (Botelho et al., 2017).

In addition, integrating "more-than-human" design principles into urban planning and sound design is essential for recognizing the interconnectedness of human and non-human elements within urban environments (Pavlović, 2023). Democratic design emphasizes participation, equity, and the active involvement of stakeholders in the design process, ensuring that solutions reflect the values and preferences of all community members. This approach aligns with the principles of human-centric design as it prioritizes user experience and community engagement. More-than-human approach emphasizes that design should not only cater to human needs but also consider the ecological and social systems that coexist within urban spaces. By acknowledging the agency of non-human actors—such as animals, plants, and even urban infrastructure—designers can create more sustainable and inclusive environments that benefit all inhabitants. Moreover, the concept of more-than-human design aligns with democratic design principles by fostering inclusive participation in the design process. Engaging diverse stakeholders—including community members, environmental advocates, and urban ecologists—can lead to more holistic solutions that address the needs of both human and non-human residents. For example, participatory design workshops that include discussions about the acoustic environment can help identify community preferences while also considering the impacts of noise on local wildlife (Balderrama et al., 2022). This collaborative approach not only enhances the relevance of sound design solutions but also promotes social and ecological resilience.

In conclusion, the principles of human-centric design, co-creation, and interdisciplinary collaboration are essential for developing effective and appealing SWT solutions. In addition, soundscape evaluation in urban contexts highlights that the design of outdoor spaces should consider the acoustic environment to enhance user experience and reduce annoyance. By prioritizing user experience and engaging communities in the design process, urban technologies can be more effectively integrated into the urban fabric, ultimately leading to sustainable and socially innovative outcomes. Table 3 contains a correlation of these design principles with the points mentioned at the beginning of the discussion.

5 Conclusion

The integration of small wind turbines (SWTs) into urban energy systems offers a promising path toward sustainable and democratized energy solutions. By addressing technical challenges, prioritizing human-centric design, and fostering interdisciplinary collaboration, these systems can overcome existing barriers and contribute to resilient urban communities. Emphasizing community involvement and ethical considerations will not only enhance acceptance but also pave the way for a more inclusive and sustainable energy future.

Our analysis reveals critical pathways for advancing SWT integration through human-centered design:

1. Develop interdisciplinary design teams combining expertise in engineering, urban planning, and social science to address both technical and social dimensions.
2. Implement standardized participatory design protocols for SWT projects, ensuring community engagement from conceptualization through implementation.
3. Create modular, adaptable SWT designs that respond to diverse urban contexts and user needs.

TABLE 3 Design strategies that can be adopted for SWT success.

Critical factors	Concerns	Objective	Design strategy
Active community engagement, participatory design, and demonstration projects	End users as decision-makers	Involve end users in the design process, Participatory process	Co-creation, assemblage thinking
Address local concerns	Visual	Architectural and cultural values, landscapes	Value-sensitive design
	Audition	Technology noise mitigation	Sound design, more-than-human design
	Level of technical skills	Human centric-design principles	Assemblage thinking
	Motivation	Social innovation	Comprehensive anticipatory design science, vision in product design
		Empowering community	
	Financial resources	Socio-economic feasibility	Circular design, value-sensitive design
	Social recognition	Identification and sense of ownership	Co-creation, assemblage thinking
Comprehensive frameworks	Technological perceptions	Social learning and dialogue	Value-sensitive design, assemblage thinking
Transparency and communication			
Sustainable and lifecycle management	Lifecycle impact	Sustainable transition	LCA and circular design, value-sensitive design, assemblage thinking, more-than-human design
Policy and regulation support	Energy independence	Trust	Democracy design
Socio-economic accessibility	Equitable and inclusive solutions	Prevent marginalized communities, human-centered renewable energy transition	Co-creation

4 Establish clear metrics for human-centered success factors (community acceptance, accessibility, perceived value) alongside technical performance measures.
5 Develop policy frameworks that incentivize both technical innovation and social integration.

These recommendations provide a foundation for stakeholders to transform SWT implementation from a purely technical challenge to an opportunity for community empowerment and urban sustainability.

Promoting energy democratization, SWT systems have the potential to democratize energy access by enabling local generation and self-consumption. Unlike large-scale energy projects, SWTs can empower individuals and communities to actively participate in the energy transition. This aligns with broader goals of social equity and environmental justice as it allows marginalized groups to benefit from renewable energy innovations.

Moreover, the sustainability of SWT solutions must be evaluated in terms of their full lifecycle. Efforts to minimize the environmental footprint of these systems, i.e., using less environmentally impactful materials and improving energy efficiency, are crucial. Ethical considerations should guide the deployment of SWTs to ensure they contribute to a just and equitable energy transition.

Finally, the study emphasizes the need for interdisciplinary collaboration to address the complexities of urban wind energy, indicating a methodological framework that incorporates insights from various fields such as design, engineering, and social sciences.

5.1 Limitations

Technical limitations, such as optimizing turbine placement in dense urban environments and mitigating noise, must be overcome. Equally important are the social challenges that arise from their implementation, including the perception of SWTs as intrusive or unsafe. Engaging communities early in the planning and implementation phases can mitigate resistance and foster a sense of ownership. In the same manner, providing clear information about the benefits and addressing misconceptions are critical to overcoming these barriers.

5.2 Future work

Future studies should focus on prospective evaluations of wind turbine systems to assess their long-term impact on urban energy systems and the wellbeing of communities. Improved modeling techniques, such as computational fluid dynamics (CFD), can improve understanding of urban wind patterns and optimize turbine performance. In addition, research should investigate the scalability of SWTs and their integration with other renewable energy systems, but all of this must involve collaborative work that considers human values before technological ones.

Future research should focus on quantifying the socio-economic benefits of human-centered approaches and developing standardized tools for participatory SWT design processes. There is also a need for longitudinal studies to examine how community perceptions and engagement with SWTs evolve over time, providing insights into long-term adoption and integration strategies.

To maximize the potential of SWTs in urban environments, it is recommended to seek the applicability of the strategies or tools that have been proposed in the discussion section. For example:

- Develop modular and customizable designs to respond to urban geometric diversity.
- Create clear guidelines and regulations for integrating steel cables into architectural and cultural contexts while minimizing visual impact.
- Encourage interdisciplinary research to explore innovative wind flow modeling and noise reduction technologies.
- Work on a design where sound is predefined by its forms and materials and defined by some participatory process where the degrees of auditory disturbance are assessed according to the context.

Moreover, an analysis of current products on the market is needed to get a more realistic view of SWTs and how they are being accepted in society. The business world often responds to user needs through a process of iteration that can be informative for the academic world.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. AR: Data curation, Funding acquisition, Methodology, Supervision, Validation, Visualization, Writing – review & editing. OU: Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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