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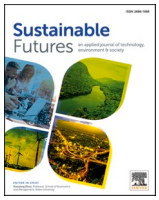

Co-creating sustainable innovations in Irish social housing through participatory research

Tracy Mae Ildefonso, Valesca Lima *, Stephen Daniels, Joseph Mullally

Dublin City University, Ireland

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ABSTRACT

Policymakers need active citizens' participation to implement meaningful, transparent, and inclusive reforms aimed at ambitious policy changes. However, effective methodologies for ensuring genuine participation, addressing inherent power imbalances, and translating community stakeholder feedback into tangible and lasting policy and project outcomes remain underdeveloped, particularly within the context of housing sustainability and innovation in Ireland. This research addresses this critical gap, employing Participatory Research methods, engaging 28 stakeholders in the Irish social housing sector to inform the implementation of environmental sensor technology to enhance housing sustainability and resilience in the industry. This study details the insights collected from stakeholder engagement, focusing on key concerns, such as data privacy and the diverse needs of residents. It also demonstrates how this input shaped the project's technological design and engagement strategies. The insights shown in this research aim to motivate researchers and policymakers in Ireland to adopt participatory approaches that integrate citizen perspectives into digital innovation and resilience planning. This research also contributes to the field of participatory research methods with a practical approach to meaningfully engaging vulnerable populations and integrating their concerns into technological solutions, demonstrating how participatory frameworks can advance both digital sustainability and housing resilience.

1. Introduction

Stakeholder engagement provides policymakers with valuable insights into policy impacts and strengthens the legitimacy of significant changes. Especially in the field of housing sustainability, practical and effective methods to ensure meaningful participation, address power imbalances, and translate stakeholder input into tangible policy and project outcomes remain underdeveloped. Recent research in Ireland on social housing and sustainability projects, covering construction [1], urban development [2], regeneration projects [3] and public-private partnerships (PPPs) [4], highlights the critical need to involve all stakeholders throughout projects lifecycle, as its absence can seriously affect program planning, implementation and outcomes. For example, the housing and urban regeneration plans proposed by Dublin City Council in 2004, launched under the National Development Plan (NDP) (2000–2006), were strongly criticised for the lack of meaningful consultation and participation. The residents were uprooted and then left in limbo without their voices being heard both during the design phase and once the PPPs collapsed due to a lack of agreement stemming from inadequate public consultation, further complicated by the global financial crisis [5,6]. Additionally, implementing sustainable urban development projects in cooperation with various Local Authorities (LAs) in the Dublin region presented significant challenges due to a lack of regional cooperation and communication [2]. This resulted in an absence of a unified vision for addressing project goals, stemming from each organisation's varying aims and priorities, stunting the project's progress.

While stakeholder engagement has a critical role in project legitimacy and is paramount for project success, truly involving all stakeholders through meaningful participation is challenging. Approaches to this normally move beyond mere consultation, fostering the mutual understanding and transparency that Sheppard and Beck [7] identify as crucial for encouraging stakeholder support and mitigating potential disengagement. For organisational stakeholders in areas like housing regeneration, developing a sense of shared goals and responsibilities, as shown by Winston [8], is vital for minimising individual self-interest and ensuring project outcomes genuinely align with the diverse needs of the community. A deep and meaningful engagement addresses the public

* Corresponding author at: Henry Grattan building, Glasnevin campus, Dublin City University, Glasnevin, Ireland.
E-mail address: valesca.lima@dcu.ie (V. Lima).

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stakeholders' demands for transparency, accountability, and opportunities for consultation, thereby contributing to public policy development related to the project, while enhancing and accumulating public trust [4].

Several projects in the Irish government have successfully exemplified successful stakeholder engagement achieved through a combination of participatory methods, such as public discussions, panels, open discussions via debates and communication lines through phone or email, and information dissemination through webinars, mass media, or in-person meetings and workshops. For example, a sustainable development initiative involving LAs in Dublin included all stakeholders throughout the planning and management process [2]. This approach encouraged a sense of ownership among participants, enhancing collaboration and motivation among LA staff. As a result, their recommendations were integrated into the 2013 Sustainability Report of Dublin City Council for future initiatives. In a different project where social housing tenant consultation was prioritised as a means of effective communication within the sector, Jordan [9] observed that the dialogues and narratives from the tenants shifted from blame to constructive problem-solving, resulting in residents feeling valued, engaged, and included in the social housing-related decision-making process. Lastly, when the Department of the Environment, Climate and Communications conducted public and organisational consultations in redesigning the Energy Efficiency Obligation Scheme, it helped create their policy decisions that addressed the tailored needs of the population, such as enhanced support for those facing energy poverty, as confirmed by a residents' survey (see [10], p. 29–32).

Existing research recognises the critical role of public participation in policy design and implementation, but it often faces criticism. Its policy-making impact is often considered to be minor, limited, and difficult to measure, as members involved in discussions tend to be a small segment of the community and may not fully represent the entire population's diverse needs [11–13]. Public forums, for example, can be prone to manipulation, as the spaces for assembly, the agendas, and the information shared can be controlled by those facilitating the discussions, leading to challenges in effective and authentic deliberation, especially if the participants' knowledge on topics discussed is limited (ibid.). The results gathered from these forums can also be undermined, particularly when the ultimate decision-making authority is confined within institutional frameworks [14].

Moreover, there are cases wherein active public participation did not yield the expected favourable results. For example, the Dolphin Housing case, a social housing apartment complex in Dublin [15]. The residents began advocating for its regeneration in 2005 due to poor living conditions caused by severe mould problems and other environmental issues. After one rejection and a decade of gathering substantial empirical and scientific evidence, which included involving LAs and consulting experts to highlight the urgency of the situation, as well as several court proceedings (ibid.; [16]), the government finally responded in 2016 by allocating €25 million for the project. However, despite this development and a master plan created four years ago, only a quarter of the property has been retrofitted, leaving the majority of it in the same dilapidated state as it was twenty years ago [17].

Similarly, the public housing complex O'Devaney Gardens in Dublin also engaged the community in calls for regeneration during the 1990s [3]. The residents were active in campaigns for housing regeneration and lobbied against the local government's decision to demolish the property. However, before the project was halted in 2008, several residents had already relocated to make way for the construction. This premature cancellation diminished the residents' enthusiasm to continue advocating for the project, leading to a weakened community spirit due to proximity loss among neighbours. Talks of repurposing the property started in 2016, but to convert it into a commercialised residential rental area. Unfortunately, the local government did not consult the original residents and advocates in this decision (ibid.).

Despite criticisms, experts argue that PR is still relevant and will continue to be applied in decision-making processes. Even the commercial sector focusing on green servitization to create an organisational management approach on sustainability issues also recognises the importance of a holistic approach in developing effective business models, including society's expectations in using their products [18]. An effective servitized business model has the potential to influence public policy decisions or create new environmental norms, thus inspiring behavioural changes in society (ibid.). Hence, the focus should shift to enhancing effective public forum strategies to maximise their impact on policy development [14,11,13,19]. For example, Poole and Elstub suggest "filtrations" during mini-publics: filtering ideas, perspectives, agendas, and any information during the policy process that comes from the system, whether they are political, institutional, or organisational ([19], p. 03). Pogrebinschi [13] recommends scaling the participatory deliberation process to a national level by creating a bottom-up design that includes all stakeholders, particularly civil society, throughout the participatory process; while Holdo [20] argues that legitimate, genuine citizen engagement supports democratisation when it contributes to aligning elite and citizen interests, including in times of crisis [21]. Thus, despite recognised challenges, the scholarly consensus goes towards a link between aligned interests and democratisation through genuine engagement, underscoring the imperative to refine public participation strategies that guarantee sustained and meaningful citizen influence at all stages of policy development.

In line with this, calls to involve all stakeholders in public projects in Ireland are increasing, as many believe this is a key factor in achieving project success and addressing the gap in utilising this practice across the country [2,4,6,15,22,23]. Hence, this paper contributes to the growing literature on participatory research approaches, specifically within the context of housing sustainability and the integration of environmental sensors in social housing in Ireland. It sets out to answer the following research question: How can we effectively engage social housing residents in utilising sensors and ensure their ongoing participation while collaborating with them and social housing organisations to develop robust policy recommendations for asset maintenance incorporating sensor technology?

This paper discusses the outcomes of stakeholder consultations stemming from the application of PR strategy to our research project from the outset. By doing so, we align our policy maintenance solution with the needs of stakeholders, specifically tailored to the current context. Our preliminary empirical analysis has yielded insights that significantly influence the design of our proposed technological innovation to promote housing sustainability in Ireland's social housing facilities. These designs address the diverse needs expressed by all parties while ensuring the technology remains low-cost, non-intrusive, and suitable for incorporation into policy recommendations aimed at enhancing residents' health and asset maintenance strategies within the country's social housing sector.

This article has seven sections. The introduction section is followed by the study's background and the main project from which the data is derived. The next section presents the theoretical framework, emphasising a participatory approach in sustainability projects. The methodology follows, leading to the results that consist of three sections: issues on data privacy and management, resident participation for general needs individuals, and resident participation for those with specific needs. The discussion reflects on how the collected data influenced the project in the aspects of technical and resident participation plans. Lastly, the conclusion provides answers to the research question and additional recommendations based on the findings.

2. Background of the Study: The SHINE Research Project

The project, "Sustainable Homes Integrating Non-Intrusive Environmental Sensors" (SHINE), adopted PR during its initial stages. SHINE aims to enhance the environmental health and resilience of Irish social homes and their residents through environmental sensors and policy

shifts related to proactive maintenance. As part of a technological intervention project designed to improve the health and living conditions of social housing residents, while also promoting their proactive sustainability practices, we assessed social housing stakeholders' receptiveness to the sensor development proposal.

The need to address environmental and sustainability issues in this sector stems from recent findings in Ireland that reveal poor health outcomes among social housing residents due to unsatisfactory indoor environmental conditions [15]. Mould infestation, in particular, has severely impacted children, older people, individuals with respiratory conditions, and even healthy residents, ultimately deteriorating both their physical and mental health [24–26]. Research also shows that consistent exposure to harmful indoor elements, such as mould and particulate matter from burning wood for indoor heating, can lead to serious health consequences, including death [27,28].

SHINE is developing a low-cost, non-intrusive, all-in-one environmental sensor designed to detect potential issues before they arise by gathering real-time data on the residents' indoor environment and analysing their indoor behaviours that impact their home environment conditions. This sensor is expected to inform policy strategies for Ireland's social housing authorities to transition their property maintenance approach from reactive to proactive. Reactive means responding to housing maintenance issues only when reported, while proactive means maintaining housing conditions to detect possible problems before they manifest. This can be aided by a technological tool, such as the SHINE sensor, which detects air conditions at home, such as humidity and nitrogen dioxide (NO2), contributing to cleaner and healthier home environmental conditions for the residents. This strategy has the potential to enhance the sustainability and resilience of social housing infrastructure in the country by keeping it to high standards that can withstand future environmental challenges.

In Ireland, social housing providers are responsible for providing repair and maintenance services to their residents, addressing issues such as dampness, mould, and condensation, and effectively acting as landlords for residents. Currently, their maintenance strategy is reactive, meaning they only respond to problems once they are reported. This reactive approach risks residents to prolonged exposure to harmful conditions before the issues are resolved, simultaneously compromising the integrity of the infrastructure. SHINE will provide a sensor that can inform a proactive maintenance strategy, which focuses on identifying and addressing problems before they manifest. The SHINE sensor will play a crucial role in facilitating this shift, particularly in newly built and retrofitted homes, as it can help reduce time, health risks, and repair expenses while minimising and eventually eliminating home energy inefficiencies.

IoT systems used for property management and smart home enhancements, such as energy optimisation and predictive maintenance, have led to a significantly positive tenant experience rate [29]. The real-time analysis of power usage by smart IoT systems has resulted in a 20–38 % reduction in energy consumption, improved air quality at home, increased comfort, and better communication between tenants and landlords regarding maintenance issues (ibid.; [30]). According to Ahmad and Alshurideh [30], tenants tend to trust these systems more, as real-time surveillance allows staff to send alert messages to tenants' mobile devices in the event of issues such as security breaches or air quality concerns. Additionally, the shared control of the system, where tenants can manage room temperature and landlords can oversee remote management, fosters a positive relationship between the two parties, enhancing the user experience of this innovative home management protocol (ibid.).

These benefits also extend to the management level. Research by Oladoja et al. [29] demonstrates that the use of IoT devices in homes decreases unplanned maintenance and emergency repairs, as they can predict future structural problems. Consequently, this has helped lower maintenance costs, prolong the lifespan of properties, and improve management functions by streamlining reports and data (ibid.). It is envisaged that such a maintenance approach could provide governments with annual savings of €555 million for Catalonia and €758 to €930 million for France toward housing management and health care costs [31]. In Bangladesh, predictive analysis from data collected through IoT systems related to "stress, strain, and environmental impacts on concrete structures" has allowed for proactive solutions to potential future catastrophic issues ([32], p. 81). Furthermore, the system has recorded an additional 30 % of anomalies that traditional surveillance could not monitor, highlighting the effectiveness of these technological systems in the preventive maintenance of property structures (ibid.). SHINE aims to replicate these results through its low-cost sensor and policy recommendations, as inspired by findings from PR.

From the project's onset, we identified potential implementation challenges. First, we pinpointed residents' scepticism towards sensors because of concerns regarding the intrusive nature of other sensors that can monitor indoor behaviours, track the number of occupants, and record visitor frequency at specific times and days, which raises significant privacy concerns [33,34]. These concerns are valid, and so we conducted a comprehensive analysis of existing sensor technologies: sensors and other IoT (Internet of Things) devices can collect personal and sensitive data that is vulnerable to attacks when transmitted over Wi-Fi, possibly leading to data theft [35,36]. Additionally, there is a lack of available data regarding discussions on Irish social housing, particularly involving residents from various socioeconomic backgrounds [37]. Studies on IoT systems implemented for vulnerable populations living in smart homes were also taken into account. For example, ethically managing their data should be strictly regulated by the government to ensure it is received by the appropriate authorities for health and security purposes [38]. This means that the data of a person with a disability should be sent to healthcare facilities for assistance, rather than to private companies that could take advantage of the information (ibid.). Designing tools ethically can also be achieved through accessible designs and by integrating them into the planning process to satisfy customised needs and foster inclusivity [39]. For example, home automation systems that use sensors and actuators designed for people with disabilities to operate home appliances like washing machines can also be utilised by the general population (ibid.). Lastly, several advice on transmitting the vulnerable group's data securely, such as encryption and decryption techniques for accessing data stored in the cloud, were reviewed and applied in the analysis [40]. The data informed the development of our sensor design that prioritises data security and resident privacy, and made the team aware of the risks and limitations to gathering insights that are tailored to the specific needs of the Irish population.

The SHINE sensor design was significantly informed by advancements in IoT literature that emphasise user privacy and data minimisation [36,41,42]. By examining various case studies, we identified key functionalities that enhance user experience and efficiency [43]. This inspired us to focus on modular designs that seamlessly interact with existing IoT ecosystems, ensuring scalability and adaptability for future technological advancements [44,45]. Integrating findings from studies on edge computing and local data processing, such as Fedora, ThingsBoard, Balena, Stack Overflow, and GitHub for mould risk index integration, enabled the team to develop a sensor system that minimises unnecessary information transmission, ensuring that sensitive data remains within the household while still providing valuable insights for residents and stakeholders. Further analysis of our IoT findings and how they influenced our sensor designs is also available online [46].

Furthermore, we developed strategies to effectively communicate with residents that we may apply in future pilot stages or sensor testing, as we understood the challenges of presenting technical data to residents in a way that is easy to understand, to encourage active home sustainability practices. We also consulted with industry and academic experts to better understand how they have addressed such issues in their previous projects. Collaborating closely with our project's societal impact champion, Clúid Housing, the largest Approved Housing Body (AHB) in

Ireland, was a project partner and offered real-time, grassroots insights into the current technology, sustainability, and environmental issues affecting social housing residents, which was beneficial in shaping our solutions. Research has shown that the anticipated outcomes are not achieved when there is no connection between the data collected and the users' specific behaviours and needs [47]. Hence, these strategic collaborations and considerations led us to prioritise and secure social housing residents' participation as a key factor for the legitimacy of the proposed new technology and successful sensor adoption in the future.

3. The Participatory Approach in Sustainability Research

This section discusses a dual trend in the literature: the growing adoption of Participatory Research (PR) to strengthen research impact in fields such as sustainable development and smart cities, and the critical examination of its practicalities and limitations for a more nuanced understanding.

3.1. Participatory Research: Power Dynamics, Sustainability, and Smart Cities Challenges

Power dynamics are a salient element often observed in participatory spaces. PR distinguishes itself from conventional approaches through its focus on achieving actionable results by early and sustained involvement of local individuals from the outset [48]. In conventional research, ideas are typically formulated by researchers, academics, and practitioners, which centralises the power of inquiry in their hands. In contrast, PR involves local people not only during data gathering, but throughout the process, including planning for the framework, methodology, research questions, findings, and ownership of results. The ultimate goal is to create an environment where scientific information and local knowledge are integrated, making the research more relatable to public stakeholders (ibid.). Bartels [49] argues that stakeholder engagement should focus on enhancing communication strategies and approaches that advance the project, rather than on communication alone, as the latter often lacks a structured framework. Ritchie et al. [50] further highlight that using an iterative approach when engaging communities in data collection and forming an advisory group not only yields a targeted focus on developing actions that meet specific community needs but also fosters a sense of shared and equal power dynamics between participants and researchers.

The emphasis within PR on achieving practical, useful results grounded in local needs [48,50] finds particular resonance within the field of sustainable development. In sustainable development projects, Hedelin et al. [51] emphasise that participatory planning can help bridge the gap between science and policy, and scientific knowledge with contextual understanding using effective communication strategies. They argue that these gaps can be bridged when communication with all stakeholders is enhanced through innovative tools, such as "visualization tools and computer based simulations, e.g. of different scenarios showing cause-effect-relationships in an understandable and transparent way" (p. 192). This approach fosters mutual knowledge exchange and integration between experts and local stakeholders while ensuring that local participants are well-informed about the complex aspects of the projects being implemented. These examples underscore the literature's exploration of PR as a means to empower communities, integrate knowledge, and achieve more relevant outcomes for all involved.

However, alongside the enthusiasm for PR, another significant trend in the literature is a critique of its practical implementations. Solutions normally focus on the mechanisms to improve the effectiveness and equity of PR. For example, as discussed earlier, Poole and Elstub [19] found that the filtration process in enhancing PR helps prevent agendas from infiltrating public forums. Similarly, Lawrence et al. [52] argue that when a sustainability project impacts stakeholders' health, environment, and safety, it should follow two important procedures: sustainability filters (SF) and sustainability enhancers (SE). Despite being similar filtration strategies, they differ significantly depending on the project, with the SF process being presented as more suitable for sustainability studies. While SF also involves consulting all stakeholders from the planning stage to completion to address any concerns they may have, it should always be complemented with SE. SE focuses on ensuring that the intervention (i.e., technological tools) meets the 5 A's: Adaptable (easily modifiable), Affordable, Available (i.e., spare parts for easy maintenance), Applicable (capable of addressing the problem), and Appropriate (relevant to the stakeholders' situations) (p. 335). Overall, Lawrence et al. [52] recommend the integrated implementation of both SF and SE in sustainable development project planning involving interventions. This integrated approach ensures robust stakeholder involvement and appropriate design planning that caters to stakeholders' needs and identifies potential dislikes and weaknesses from the outset, ultimately helping to improve the features, interface, and maintenance of interventions.

In the field of smart cities, adopting PR in designing technological innovations that will impact citizens has shifted from a technocentric approach to a human-centric one, prioritising user-end experiences such as ease of use and comprehensibility [53]. For example, a workshop involving older adults as end users was conducted to aid in formulating policy recommendations for creating an age-friendly city aimed to enhance their urban living, through gathering data and utilising technological tools, like disruptive technologies for an improved and safer street mobility experience [54]. Participatory governance, allowing public access to government data and policy-decision processes, is also being applied in smart city projects in Spain and the Nordic countries [55]. Furthermore, cities like Madrid and Malaysia have advanced this concept by implementing e-participation, where information is accessible, government representatives are available for consultation, and decision-making processes are kept transparent through their online and mobile app platforms (ibid.). Moreover, PR has played a significant role in fostering inclusive smart city projects on mobility in Brussels, as stakeholder participation revealed that proposed ideas were not universally suitable, leading to the identification of an effective solution: a combined approach of technological innovations and an e-platform for ongoing consultation and updates [56]. There is also an emerging call to consider nature when engaging in the participatory design of smart city projects. Tomitsch et al. [53] argue that non-human stakeholders should be factored into the planning processes. For example, in Sydney, consideration for native species like possums, birds, bees, and plants impacted by smart urban furniture or green space initiatives necessitates provisions for alternative food sources and relocation options (ibid.). Of note, the commercial sector has leaned towards a service-based business model, such as sustainable servitization and Product-Service Systems (PSS), to encourage sustainable practices [57]. However, limited stakeholder insight often reduces their environmental impact, highlighting the need to consider stakeholders' requirements and needs [18].

However, some findings from PR scholars regarding sustainability project planning emphasise the need for careful consideration of the realities and complexities of implementing participatory methods, paying attention to the disadvantages. In doing so, they examine practical challenges and limitations related to engagement, integration of diverse views, and the assumption that participation is a universal solution. Cornwall and Jewkes [48] argue that people may not always be willing to participate in research projects because it can be time-consuming and perceived as significant work. Hedelin et al. [51] state that integrating stakeholders' insights into research presents challenges in deciding which opinions should be included and discarded. Kanyamuna and Zulu [12] take a pragmatic approach, arguing that participation is not the ultimate solution to the problem for several reasons. First, minorities or stakeholders from the community's lower strata may be largely overlooked during consultations, primarily due to a lack of expertise regarding the project and the prevailing power dynamics. Additionally, the authors highlight little evidence of public

empowerment resulting from participation, suggesting that PR tends to be more effective in smaller-scale projects rather than in larger initiatives, such as sustainability projects, corroborating earlier cited criticisms by Pogrebinschi [13] and Elstub and Khoban [11]. The analysis of Malaysia's smart cities e-participation initiative reveals limited progress, as the government fails to update the platforms and engage citizens, leaving their inquiries unanswered, prompting Lim and Yigitcanlar [55] to conclude that the observed top-down approach is ineffective for citizen participation. In these contexts, Avritzer's [58] argument is pertinent: citizen participation only makes a significant impact when it is well-supported by a political system.

The Dolphin Housing and O'Devaney Gardens cases, discussed in the Introduction section, illustrate how power dynamics shape public consultation outcomes. Bartels [49] notes that public engagement can be manipulated by those in power, often leading to actions only when authorities choose to act. Hence, Bartels emphasises the need to establish whether stakeholder discussions will follow a 'Community' or 'Planning' narrative before any engagement commences. The 'Planning' narrative seeks collective agreements within a structured framework, while the 'Community' narrative allows for flexibility but may undermine public trust due to perceived inconsistencies. When applying these ideas to the Dolphin Housing and O'Devaney Gardens projects, it appears that Dolphin Housing employed the 'planning' narrative in their stakeholder consultations and regeneration project planning. The contrasting outcomes of the two projects, where Dolphin Housing achieved success despite a lengthy process, indicate that the organisation maintained rigidity in its project planning and implementation. The multiple court proceedings initiated by Dolphin Housing advocates, both locally and internationally [15], were strategic tools used to challenge the government's usual communication routines towards the regeneration project (i.e. frequent delays), ultimately yielding favourable results. This stands in stark contrast to O'Devaney Gardens, where the planning approach lacked rigidity, leading to an inability to develop strong project strategies and relationships among advocates over time. Bartels states that "failing to delve into the tension between the underlying narratives of Community and Planning, they will tend to engage with their situation by upholding antagonism and stalemate between those in favour of starting from scratch with a new, comprehensive institutional design and those against the imposition of an external and artificial framework on local practices," which is the current situation of the said project (2015, p. 211). Thus, understanding the differences between these strategies during the project's PR planning stages is essential to avoid conflicts in stakeholder discussions, achieve successful engagement, and meet post-PR targets, especially if the aim is to tap into political commitments.

This article, therefore, combines these important insights from PR studies and contributions from sustainability literature to consider not only how PR potentially benefits projects involving sustainability but also a nuanced understanding of when and how PR can be most effective. Reflecting on expert ideas about PR reveals that an effective sustainability project requires a more balanced power among all stakeholders, including local participants, and leveraging political will. Given the growing interest in smart home technologies and calls for better engagement with stakeholders, the PR approach is particularly helpful for sustainability projects. Hence, a key question emerged: How can we effectively engage social housing residents in utilising sensors and ensure their ongoing participation, while also collaborating with them and social housing organisations to develop robust policy recommendations for asset maintenance incorporating sensor technology? The following sections outline the methodologies and key findings.

4. Methodology

From the start, consultations with all stakeholders in the social housing sector were identified as the project's primary method for data gathering. The aim was to gain insights into their needs, challenges, the solutions they propose based on their personal experience and expertise, discuss indoor environmental and health issues, introduce the new environmental sensor, collect their feedback, assess their willingness to participate in future activities and determine their preferred methods for receiving information from the sensor.

Between January and August 2024, one-on-one online interviews were conducted with a total of 28 stakeholders from various housing organisations, in the government (LAs) and non-government organisations (AHBs), building construction companies, surveyors, non-profits, private entities, advocacy groups, and social housing residents. Separate per-person interviews were conducted to ensure participant anonymity. The participants were determined via stratified random sampling, ensuring that they represent a variety of services in the social housing sector. This is to ascertain that the diverse backgrounds in the industry are covered, from general needs to specific needs. The participants were given plain language statements, informed consent forms, and sample questions before the interview. The documents informed them of their participation rights in the project, including withdrawal of participation at any point of the project, and that it would be an unstructured conversation. Questions were non-leading and mainly about the general problems in the social housing sector, the environmental aspect, and their insights about the SHINE sensor. The discussions were further guided by the information that each participant shared. The interviews were recorded, transcribed, and analysed using NVivo software, applying thematic analysis to identify key themes. They also willingly signed their informed consent forms.

Table 1 summarises the background of the research participants. One challenge faced was recruiting a sufficient number of residents to participate. Due to privacy concerns, residents can only be contacted exclusively through their tenant engagement officers. With the valuable support of the project partner, Clúid Housing, we were able to reach out to residents and ultimately achieved resident saturation, allowing us to conclude the interview process.

Thematic analysis was applied as it provides a structured yet flexible approach to qualitative data analysis, making it an ideal choice for research focused on understanding complex social phenomena and stakeholder perspectives [59,60]. We collected a substantial amount of data, and thematic analysis allowed us to organise various stakeholders' ideas without losing the essence of the original dialogues. Using NVivo, we minimise bias by conducting multiple analyses of the interviews and applying several codes to categorise and organise the extensive ideas. An example of the coding categories involved problems related to social housing, which included subcodes such as financial problems, maintenance issues, environmental concerns, and others. All ideas presented by the stakeholders were thoroughly categorised according to the topics they discussed. In some cases, multiple codes were applied to a single opinion when they aligned with existing codes. For instance, when stakeholders mentioned challenges in maintenance due to budget constraints, those issues were classified under both the financial and maintenance subcodes.

In our analysis of stakeholders' overall views regarding the sensor, we identified three key themes related to potential challenges in project implementation: data-related concerns and resident cooperation for the general and specific needs.

The sensor development commenced shortly after determining these three issues. This approach helped the team ensure that our technological solution was tailored specifically to address our stakeholders' indoor and environmental issues in social homes, particularly focusing on preventing mould buildup and addressing any personal concerns they might have regarding sensor utilisation. Furthermore, the insights obtained from our stakeholders guided us in finding ways to create strategic plans to encourage social housing residents to participate in our future pilot projects, incorporating their proposed solutions to guarantee our project proceeds smoothly. Utilising PR in this research also provided us with an idea of how we could integrate circular value design and technology lifecycle alignment, particularly in responding to the

Table 1
Stakeholders' Profile.

Stakeholder	Department	Focus	Expertise	Stakeholder	Department	Focus	Expertise
1	Government	AHB Association	Policy	15	AHB	Housing & Service Provider	Senior Management
2	AHB	Housing & Service Provider	Senior Management	16	AHB	Housing & Service Provider	Senior Management
3	AHB	Housing & Service Provider for residents with specific needs	Senior Management	17	AHB	Housing & Service Provider for residents with specific needs	Senior Management
4	AHB	Housing & Service Provider for residents with specific needs	Management	18	Resident	AHB Resident	Lived experience
5	Government	Homeless Health	Team / Project Management	19	Government	Local Housing Authority	Senior Management
6	AHB	Housing & Service Provider	Policy	20	Government	Policy Organisation	Policy
7	AHB	Housing & Service Provider	Diversity, Equity, Inclusion	21	Private	Environment & IAQ	Consultant
8	AHB	Housing & Service Provider for residents with specific needs	Senior Management	22	Non-Profit	Building Association	Home Performance Index
9	AHB	AHB Association	Environmental Sustainability	23	Resident	AHB Resident	Lived experience
10	Government	Housing Organisation	Senior Management	24	Resident	AHB Resident	Lived experience
11	AHB	Housing & Service Provider	Policy	25	Private	Surveyor, Construction & Property Sector	Senior Management
12	Non-Profit	Advocacy Group	Social Worker	26	Non-Profit	Environment and IAQ	Senior Management
13	AHB	Housing Provider	Senior Management	27	Resident	AHB Resident	Lived experience
14	AHB	Housing & Service Provider	Senior Management	28	Resident	LA Resident	Lived experience

changing needs of residents, the social housing sector, and the environment. Further information, along with the three key themes identified, is discussed in the next section.

5. Results

This section summarises three key concerns identified by stakeholders regarding the SHINE project implementation. In the discussion section, we elaborate on how these findings have significantly influenced various aspects of our project, including sensor design, data protection, and stakeholder engagement planning.

5.1. Issue 1: Data Privacy and Management

After presenting the concept of the sensor during the interviews, initial concerns from the stakeholders centred around data privacy (Fig. 1). The project aimed to develop sensors that can analyse the indoor behaviours of households and provide advice unique to each household to enhance environmental quality based on their data. For example, if condensation is detected during household activities such as cooking, the sensor can estimate a possible timeline for mould build-up if the same condensation level persists indoors.

Stakeholders from the AHB sector expressed various worries about the potential intrusiveness of the sensor (Diagram 1). A major concern is the perception of being monitored. Housing body stakeholders indicated that residents might feel they are being spied on by their landlords using the sensor through chips, video, and audio recording. Also, there were fears that the data collected could be used against the residents. For instance, residents may worry that landlords will be aware if they are contributing to environmental issues at home, such as leaving the heating on, insufficient ventilation, or drying clothes indoors.

Data sharing and usage were other concerns raised. In today's digital environment, personal data is often collected and sold without people's awareness [61]. Stakeholders expressed apprehension that our sensors might be viewed similarly by residents. Stakeholder 21 from the private sector warned that the data collected by the sensor, particularly from vulnerable residents, could be misused. For instance, if this data were sold to health insurance providers, it could lead to increased insurance premiums for residents or even result in the denial of coverage altogether.

> *"Technically speaking, a lot of the data is not personal data. It's building data in the same way that smart meters are not personal data. But they could be used in combination with personal data for malintent. And ethically, we do have to be careful of that. So, for example, if you have a property with significantly poor environmental conditions, if that data found its way into health insurance providers' hands, that could be morally uncomfortable… if it affects someone's premiums or ability to get health insurance for lung conditions, if they live in a damp and mouldy home…" - Stakeholder 21, a private environmental consultant.*

Stakeholders from housing organisations have also raised governance concerns (see summary in Table 2). An LA stakeholder pointed out that landlords face limitations in installing sensors in their residents' homes due to the General Data Protection Regulation (GDPR) enforced in the European Union (EU). GDPR is a legal framework that sets forth rules for personal data collection and processing from individuals living within and outside the EU. The GDPR's strict protocols may raise legal questions for landlords regarding their authority to implement environmental monitoring in their residents' homes.

Moreover, an AHB stakeholder also raised concerns about interference (Table 2, #4). They noted that some healthcare and environmental sensors or wearable devices are designed to detect specific issues in a household and alert authorities in case assistance is needed. Such tools are typically used by social housing residents with specific needs, such as

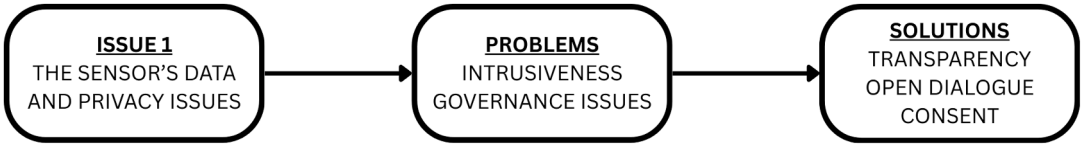

Fig. 1. Issue 1's Summary Map.

Diagram 1. The Sensor's Perceived GDPR, Data, and Privacy Issues According to Our Stakeholders.

Table 2
Possible Governance Issues of the Sensor Results According to the Stakeholders.

"There might be some anxiety when solutions are offered to problems we don't know how to solve." --- *Government Housing Organisation* (1)	"From the POV of housing organisations and local authorities, they might not want this technology because they will become responsible for this when their priority is delivering houses or maintenance." --- *AHB* (2)	"There might be some pushback from the organisations to put the sensor in social houses: who is going to pay for it, as well as the modification, and repairs of damages or issues that the sensor will detect?" --- *Government Housing Organisation* (3)	"The data and information that will be produced by the sensor that was not available in the past will raise questions: who is responding to it if a person is found to be in a risky condition?" --- *AHB* (4)
"The challenge is to get staff, organisations, government, and everybody engaged in the purchase, use, installation, and maintenance of technology." --- *AHB* (5)	"There is some reluctance to carry those out (national stock condition survey) because, in a sense, it is easier not knowing what the problems are than knowing them. Because as soon as you know the problem, you have to start fixing it." --- *Government Housing Organisation* (6)	"There is also no available infrastructure to respond to what the sensor might detect." --- *AHB* (7)	"There is a bigger issue than moisture and air quality. The sensor might create an issue with the County Council because the last thing they need is for data to be communicated in media that social houses are not up to minimum standards." --- *Private, Building Sector* (8)

older people and individuals with disabilities [62,63]. This stakeholder raised a question about who would be responsible for taking action if we were to incorporate such features into our sensor technology. These concerns reminded us that our vision for the sensor should also include a solution to these and related issues outlined in Table 2.

Concerns regarding the responsible authority for interference and insights from other interviewees on what can be considered an intrusive sensor were valuable in designing our sensor and solutions. Furthermore, in terms of intrusiveness, Diagram 2 summarises what participants considered to be intrusive.

Despite the numerous concerns regarding the sensor's capacity to protect data, the solutions proposed by stakeholders to address these issues can be summarised into three key categories: transparency, open dialogue, and consent. This is also illustrated in Diagram 3.

Transparency. The stakeholders emphasised the importance of thoroughly informing social housing residents about key details before future sensor testing begins to alleviate concerns about intrusion and monitoring. First, it is crucial to communicate the project's goals comprehensively, the sensors' purpose, and the reasons for their installation in residents' homes. One effective approach is to provide a relatable example highlighting the benefits of the sensors. For instance, residents can be informed that the sensors aim to assist in transitioning to a preventative maintenance approach for their homes, helping to anticipate and pre-empt foreseeable discomfort. A practical example given by an AHB stakeholder is that if the sensor can detect potential heating system failures, residents will receive immediate notifications, allowing them to take timely action before the system eventually fails. This narrative resonates well with residents, especially during winter months or for those facing fuel poverty, reinforcing the necessity and justification for sensor installation in their homes.

Encouraging a better understanding of the technology's limitations is vital for fostering trust in the sensor and the project among residents. From the outset, a clear and comprehensive explanation of the specific data sets the sensor collects and detects should be provided. This helps in effectively communicating the boundaries between the sensor's capability to identify environmental issues and the need to respect residents' privacy (Diagram 3, #1). Additionally, it is important to explain how data will be handled and protected. Residents should be informed about the security measures in place to safeguard their data and receive assurances that their information will not be shared with any third parties

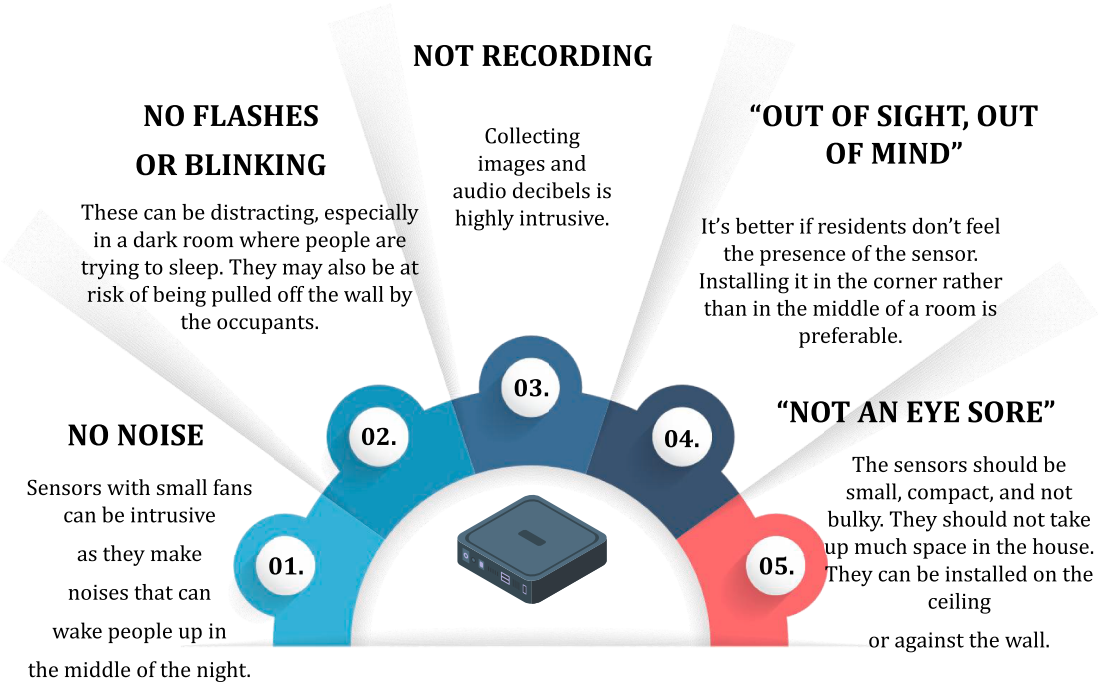

Diagram 2. Stakeholders' Description of an Intrusive Sensor.

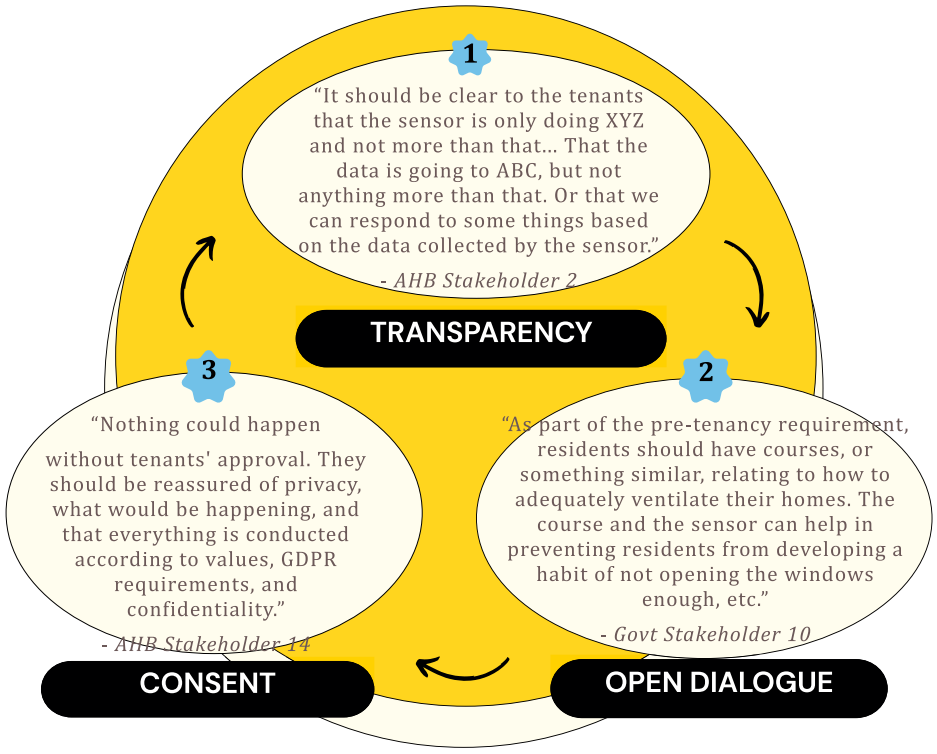

Diagram 3. The Three Key Categories of Suggested Solutions for Data Privacy Issues.

or outside the project.

An effective communication tool suggested by the AHB sector was to document the sensor's entire journey. This could involve using creative and engaging visual aids, such as diagrams or informative videos, to illustrate the process. As Hedelin et al. [51] suggested, this contributes to closing the gap between science and local knowledge. For example, showing what happens when a resident cooks without ventilation, how the sensor detects elements like CO2, where the data is sent or stored, and the alerts residents will receive can enhance understanding among residents. As such, the SHINE team heeded this advice by creating a map of our sensor's journey, which will be further elaborated in the discussions. It is also at this point that we can clarify the type of response the sensor will trigger, indicating which authority will intervene if issues are detected. Sharing this crucial information can help instil a sense of

security among residents and build trust in the proactive maintenance efforts, highlighting that the project is committed not just to data collection but also to enhancing their well-being.

Open dialogue. The project's technical and scientific nature may create a utilisation gap between residents and the sensor technology. To bridge this, it is essential to implement a two-way engagement strategy, allowing residents ample opportunity to ask questions and provide feedback. This dialogue can address concerns and misconceptions, ultimately fostering confidence in the system. A stakeholder from a non-profit organisation advocating for enhanced environmental conditions in social housing suggested that residents be actively involved in discussions about data gatekeeping, specifically regarding their willingness to share sensor data with landlords or third parties and the extent of such sharing. In an open dialogue, key terminologies—such as "non-intrusive"—along with preferences for the frequency of sensor alerts can be collectively decided upon, ensuring that the solutions developed effectively align with the residents' needs.

In instances where sensors are to be installed or are already in place, ongoing communication about proper usage is vital (Diagram 3, #2). This not only aids residents in effectively navigating the technology but also empowers them by informing them of their control over their sensor data. Importantly, it should be clearly communicated what actions residents can take with their data, the potential outcomes, and any repercussions of misuse. Hence, a government stakeholder highlighted the necessity of ethical communication, echoing SCSI's [1] strategy that emphasises respect and accountability: questions to ask the residents should be framed ethically to minimise misinformation and misunderstandings, thereby enhancing trust in the project.

Consent. The AHB stakeholders acknowledge their responsibilities and limitations as landlords within the framework established by GDPR. Hence, obtaining explicit consent for any activities that may infringe upon the residents' data privacy and protections, such as piloting an environmental sensor in social housing, should always be a priority. Our stakeholders advised us to secure residents' consent at all project stages, including data collection and installation. No activities are to be initiated without prior approval from the residents (Diagram 3, #3).

Consent may be documented through a signed agreement, ensuring all relevant information is clearly communicated and any potential concerns are thoroughly addressed. It is crucial to reassure residents regarding data privacy, emphasising the project's compliance with GDPR, the confidentiality of their data through anonymisation processes, and the steps they can take should they feel their privacy is compromised at any stage of the project. Equipping residents with comprehensive knowledge will enable them to provide informed consent or opt out of participation as they deem appropriate. It should be communicated that exercising their rights in this manner carries no repercussions, as guaranteed by GDPR, thus affirming their autonomy and rights regarding their personal data within the scope of the project. Policymakers should consider shift from digital compliance to a participation-by-design mandate. This transforms housing authorities into active facilitators of community-led digital governance.

5.2. Issue 2: Residents' Participation (General Needs Individuals)

Stakeholder consultation is a crucial first step that emerged in our analysis before implementing any projects in the social housing sector, whether through sit-down conversations, interviews, or public forums. However, the analysis also showed that there is a high likelihood that residents may use this opportunity primarily to voice complaints, instead of focusing on public consultation (Fig. 2). Diagram 4 is an overview of data we gathered regarding potential complaints, questions, and concerns that social housing residents might express during resident engagement, as indicated by our stakeholders.

Addressing this issue is where Bartel's [49] 'Planning' narrative comes into play. It is crucial to establish a structured approach during consultations; otherwise, the forum may devolve into a platform for complaints rather than an opportunity for meaningful consultation and information sharing. To facilitate this process, our stakeholders advise that we prepare answers to a fundamental anticipated question: "What's in it for us?" (Table 3, G).

The key selling point to encourage residents to participate in our future pilot program and have sensors installed in their homes is to emphasise the personal benefits they will receive. According to our stakeholders, framing this initiative as a beneficial opportunity could be persuasive. For instance, we could present it as a way for landlords to provide better services based on the data collected by the sensors. However, we must be cautious when promoting this idea, as there is a significant risk that residents may decline participation if they perceive the benefits as primarily benefiting landlords and their staff. In van Leeuwen et al.'s [54] strategy to engage older adults in their PR study, they clearly outlined how their contributions could benefit the community by combating poverty, advocating for individuals with disabilities and low-income seniors, and influencing the smart city project. Hence, our stakeholders highlight the importance of clearly communicating to the residents that the sensors can help them save time and reduce costs related to repairs, bills, and health (Table 3, B, D, H). They added that simply suggesting that the landlords will gain from the project will not be enough to convince residents to participate.

Additionally, our stakeholders recommended conducting more research on our potential participants before consultations to better understand and address their various concerns. For example, individuals who value their privacy may be hesitant about having sensors in their homes. According to our environmental consultant stakeholder, there is a lack of research in this area, leading to a limited understanding of and familiarity with the local residents' needs and preferences by the housing organisations. This gap in knowledge makes it difficult for these organisations to effectively engage residents in projects related to environmental and behavioural changes. For example, those who are not fully informed or interested in air quality may not see its relevance. While air quality is important to us, stakeholders pointed out that it may not hold the same significance for many social housing residents. Hence, this should be communicated in the preparatory phase of future sensor piloting.

Adding to the problems above, some residents are content with their current home and lifestyle habits, making it challenging to encourage long-term behaviour changes. For instance, certain residents, such as those accustomed to apartment living or people from warmer climates who are not used to the cold climate in Ireland, are less likely to open their windows for regular ventilation. Additionally, residents who lead active lifestyles, such as hosting parties, and those frustrated by being blamed for mould problems, may be unwilling to consent to having an environmental sensor installed in their homes. An AHB stakeholder pointed out that these issues stem from residents' limited knowledge about environmental matters and sensor function, which can be easily

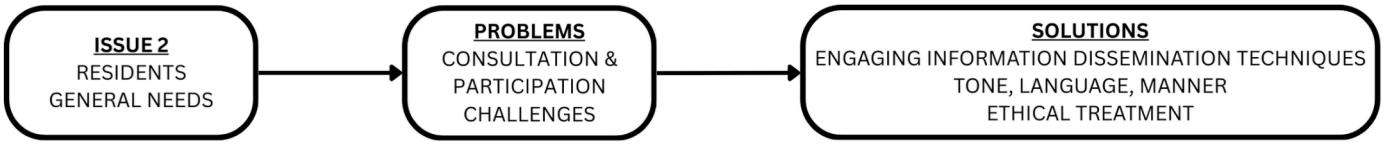

Fig. 2. Issue 2's Summary Map.

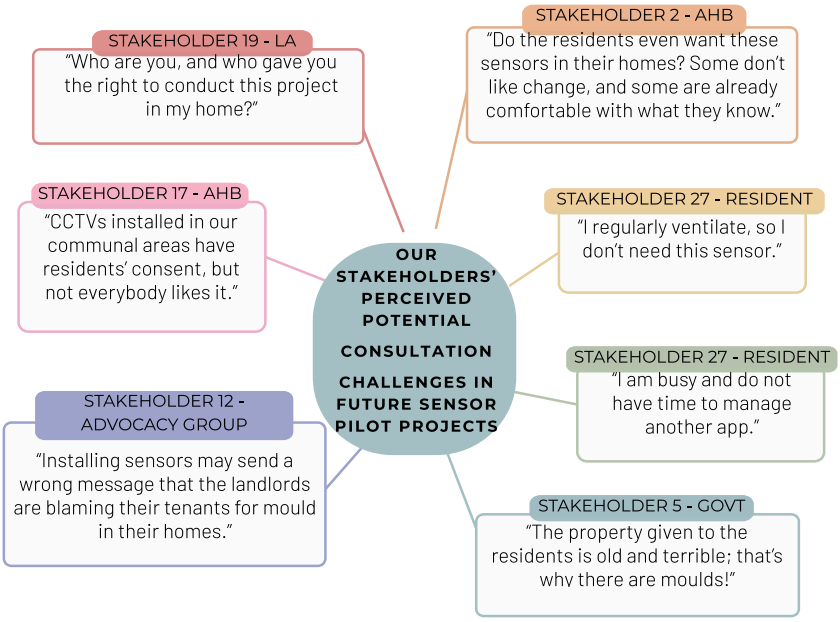

Diagram 4. Potential Consultation Challenges in Future Sensor Pilot Projects with Social Housing.

Table 3
Suggested Resident Engagement Strategies Involving Sensors.

"Explain the purpose of the sensor: to detect mould & moisture in the air, to prevent mould from forming, to help improve their lifestyle, health, and feel safer at home." *A. Government Stakeholder 5*	"Tenants should be well-informed about the sensor. So, answer these 3 possible questions: level of intrusion, what are the benefits of the sensor, what will it be capturing." *B. AHB Stakeholder 11*	**"What's in it for me?"** Narratives, such as: This technology will help them save money and ease their home living. or Explaining that the sensor can monitor if something is failing, like the heating system, so they won't be left without heating for a couple of days. *G. Theme that emerged based on stakeholders' insights.*	Mitigate the "landlord vs. tenant" challenge by making it clear that the sensor will not monitor conversations and "we're not going to come down hard if you don't open your windows." *C. AHB Stakeholder 6*	"Help tenants understand that the sensor is only monitoring their health and the health of the building to anticipate future maintenance needs." *D. AHB Stakeholder 4*
"Here is our definition of non-invasive, we're just really taking data on the building. We're not taking data on you." *E. AHB Stakeholder 8*	"We should use environmental data to inform the residents so they would know how to manage their homes better or determine if the problem is a structural issue." *F. AHB Stakeholder 15*		"It's for your own good, for your own health and comfort in your property. Then explain a clause on their lease about maintenance (not blocking vents, dry clothes outside, etc.)." *H. Surveyor Stakeholder 25*	"Explain the elements' purposes (i.e. CO_2, NO_2). Then give them very good reasons why these are monitored and how knowing these details can improve the level of comfort in their homes." *I. AHB Stakeholder 15*

addressed by communication.

In these scenarios, it is important to prioritise effective information dissemination, consultation, and communication. A catchy tagline can make our message more engaging and appealing. A stakeholder from the government sector who collaborates with social housing organisations in Ireland proposed the idea of "Help Us Help You." This tagline can be accompanied by the narrative that by allowing us to improve your air quality, you are also protecting yourself from health complications caused by harmful environmental factors in your home.

Our stakeholders strongly highlighted the appropriate tone, language, and manner of delivering information. They shared that several misunderstandings and issues between residents and landlords often stem from communication problems. For instance, the tone and narrative of blaming residents for mould issues in their properties can make residents feel attacked and defensive. This may lead to residents being hesitant to grant access to their homes, or even refusing to participate in the project altogether. Access remains a persistent challenge, as highlighted by our stakeholders in both the AHB and LA sectors. Hence, clearly outlining the goals and benefits of the project will help address this misconception. Table 3 summarises our stakeholders' suggestions on this specific matter.

Lastly, ethical treatment must always be a priority. This includes never forcing residents to access properties where they have not given consent. It is essential to always ask for permission and wait for residents to consent before entering their premises. According to stakeholders, ethical considerations regarding technical innovations should also include the following: do not make residents feel they are monitored, treated like lab subjects, or patronised. These guidelines apply to all residents, especially those with specific needs.

5.3. *Issue 3: Residents' Participation (Specific Needs)*

Residents with specific needs require additional assistance in their daily lives due to challenges that general needs individuals may not face.

This group includes people who use wheelchairs, older adults, individuals with physical or psychological disabilities, and sensory impairments. Such residents often need extra support within their homes to live independently, such as personal assistance, health monitoring, technological interventions, and modifications to indoor features and infrastructure.

Implementing projects that affect residents with psychological, neurological, and developmental conditions requires careful consideration (Fig. 3). After installing sensors in their homes, the following scenarios may occur, leading to a high likelihood that residents will remove the sensors from their properties, according to our stakeholders:

- Individuals with paranoid schizophrenia might believe that the sensor is a bugging device.
- Residents with autism spectrum disorder may fixate on the sensors on the wall or become easily triggered by the noises they produce.

Other possible scenarios to consider, particularly when addressing the specific needs of residents as identified by our stakeholders, are the following:

- Older individuals may disregard the sensor recommendations, similar to how they currently overlook advice from their housing bodies communicated through newsletters. Therefore, they may require constant reminders to engage with the system.
- Residents who have transitioned from institutional care may be suspicious of the sensor's monitoring capabilities, as they may associate it with the surveillance practices they experienced in those facilities.
- A resident with a serious health condition may feel discomfort or anxiety when receiving home environmental alerts regularly.

To promote inclusive resident engagement and mitigate obstacles in implementing technology-based projects, such as the risk of residents damaging sensors, specific actions should be tailored to the circumstances. Stakeholders recommend reviewing the legal frameworks, like the Assisted Decision-Making (Capacity) Act 2015 [64], to ensure compliance when seeking consent from residents unable to make independent decisions. For migrant residents, it's crucial to treat them equally and consult the Social Inclusion and Community Activation Programme (SICAP) [65] to prevent discrimination against marginalised communities, the unemployed, and ethnic minority groups.

Vulnerable populations, including wheelchair users, older adults, and those with health conditions, are increasingly open to technological interventions following more widespread gadget usage during the COVID-19 pandemic. An AHB stakeholder working with elderly residents noted that they have developed a strong appreciation for technology, including sensors and wearable devices, which assist them in managing their health, maintaining social connections, and ageing in place independently. Similarly, another AHB stakeholder highlighted that their residents with physical disabilities are also utilising technology to enhance their independence. This growing familiarity encourages our project's aim to enhance health outcomes for vulnerable Irish social housing residents. Thus, stakeholders recommended marketing the SHINE sensor to these groups as a crucial tool for improving quality of life, emphasising its enhanced benefits for both the environment and daily living.

> *"There are gaps in the broad spectrum of services of the housing welfare body, particularly around sensory impacts of light and noise. Your instrumentation could be very useful, demonstrating the extent of noise, neighbourhoods, traffic, environmental noise, and decibel levels that can induce deterioration of a person's chronic condition. Or could be the absence of proper light, lighting. That type of evidence would help demonstrate the need to make an assessment of a person's needs to access remedy service in health or somewhere else, primary care." - Stakeholder 20 from the government sector working on policies for sustainable advancement in Ireland.*

Other advice is to take a gentle and patient approach when interacting with residents facing mental health or neurological challenges is crucial, as they may suspect outside interference in their homes, according to our stakeholder from the government's homeless sector. The stakeholder added that it is also important to understand the different forms of autism, as some individuals may not display obvious conditions or sensory sensitivities. Aside from engaging in discussions with them and clarifying that our primary focus is on checking for mould, it can also be helpful to develop a system that aids in explaining the sensors' purpose and sensory aspects. This approach is also beneficial for residents transitioning from institutional care to social housing, addressing possible concerns about monitoring their personal spaces.

To effectively convey complex information, using images, visual aids, or videos can be helpful, making the content more engaging and informative. To address cultural or language differences, it is advantageous to provide these materials in multiple languages. Many AHB websites currently utilise the "Recite Me" [66] tool that translates web pages and provides voice-assisted reading for visually impaired individuals. This tool promotes an inclusive online environment, enabling residents to manage their tenant responsibilities easily on their landlords' websites. Additional valuable insights gathered from our stakeholders on effective ways for the team to convey the benefits of our sensor to the sector are outlined in Table 4 below.

These findings show that sensor adoption depends on addressing socio-ethical concerns rather than just technical feasibility. This evidence forms the basis for the policy recommendations discussed in the following section.

6. PR's Influence on the SHINE Research Project

The data collected was essential for developing effective environmental solutions while thoughtfully considering the critical issues of data protection and resident participation highlighted by stakeholders. This section discusses how this data was to shape the solution design, incorporating both technical and PR recommendations.

6.1. PR's Influence: Technological Solution

The solution (Fig. 4) that the project devised was a sensor box equipped with hardware designed to monitor environmental settings such as air quality, humidity, and noise levels. The box is wirelessly connected via a WiFi module to a local gateway and an IoT SIM module for complete autonomous deployments. The data is then transmitted to the SHINE software and subsequently to a cloud-based report collection platform. The SHINE box has computational capabilities to condition and analyse data and run algorithms to make decisions or recommendations, either locally or in the cloud. To put it simply, the sensor box

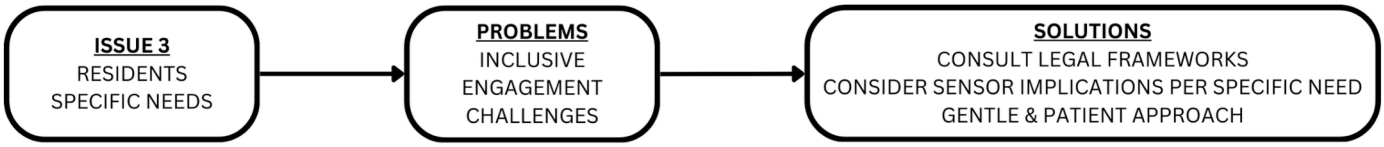

Fig. 3. Issue 3's Summary Map.

Table 4
The Sensor's Perceived Benefits for Both Landlords and Residents.

TO THE SOCIAL HOUSING LANDLORDS	TO THE SOCIAL HOUSING RESIDENTS
Lesser risk of exposure for landlords & their staff when visiting or inspecting a property, especially if they are unaware of its existing environmental problem.	To be informed of black mould build-up on the wall before anyone else can inform them.
Addressing mould problems on some providers' older units by helping them achieve their environmental requirements through the sensor.	Inform the residents if there's too much humidity or moisture, not enough ventilation, etc.
An environmental sensor can be used to monitor the environmental conditions of properties that underwent deep retrofitting, i.e. if the homes are healing, airtightness, potential radon issues.	Lesser health risk for residents, particularly respiratory issues.
Can help in sustainability and maintaining their stocks to a high standard, as well as looking after the well-being of their residents.	Data from their sensor can be used when filing for a complaint to their landlords or a public body, i.e. Residential Tenancies Board.
Transitioning from reactive to proactive or Preventative maintenance: to be able to be informed that something is about to malfunction before it happens.	The sensor can help tenants who are older people to be constantly reminded to open the window to help prevent mould build-up in their houses.
Government housing bodies cannot monitor air quality in 10,000 houses, but an environmental sensor can.	The sensor data can help with sensory issues as evidence for access to urgent remedy services in health, primary care, etc.
Sensors can help with post-construction assessment as this practice is currently lacking in the industry.	Contributes to empowering the residents and the digitisation agenda, i.e. instantaneous alerts from sensors to the user.
There are many ways the SHINE sensor can be used, including air pollution and environmental conditions due to traffic congestion, ventilation issues, etc.	Data from the sensor can help residents to file for urgent requests, such as transfers, caused by sensory triggers or anti-social behaviour in the area due to noise-related issues.

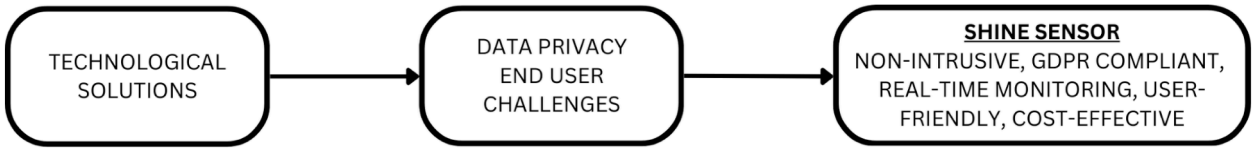

Fig. 4. SHINE's Technological Solution Map.

monitors environmental data and transmits it for analysis and potential action via local and cloud-based systems.

To address data privacy issues, such as unauthorised recording or data being sold to third parties, the design methodology focused on maximising user privacy in residential IoT sensor systems. The analytical algorithms were structured to reduce unnecessary information transmission and storage. For example, the sensor box's storage refreshes every 24 hours, eliminating the previous day's environmental data. Additionally, a goal-oriented monitoring method was implemented, ensuring that raw sensor measurements provide limited direct value where risks can be effectively managed. This design guarantees that raw measurements are not stored or transmitted; instead, onboard analytical models are processed locally, producing infrequent, low-information-content high-level reports (i.e., a score ranging from 0 to 4 every seven days). The algorithms are derived from peer-reviewed academic literature [43–45], with their implementation and functioning fully documented, transparent, and accessible to users and stakeholders. By maintaining this auditable path as the sole route for environmental data movement within the system, residents can be confident that their sensitive sensor information remains within their home and that the algorithms producing environmental reports do not unintentionally leak additional hidden data signals.

In commitment to the circular economy and technology lifecycle alignment, eco-friendly materials were used to minimise hazardous waste, while requiring low power consumption to lessen carbon emissions. The IoT system is designed to accommodate modifications for future changing needs without requiring further materials. SHINE is committed to a long-lasting environmental impact. Hence, sensor adjustments align with the eco-innovation loop and circular economy through the "reduce-recycle-recover" approach on materials ([67], p. 2). Additionally, in partnership with housing bodies, recycling plans and battery disposals with the residents are ready should the project take place.

To promote equal power dynamics among residents, the design was

focused on user data ownership and control over sharing and usage. The sensor box's ability to internally analyse and summarise 24 hours of data enables users to generate their IAQ and IEQ data locally, reducing the risk of data leakage since internet access is not required. Once the summary is complete, users retain control over their data. The box features a built-in function that enables users to send data to a third party (i.e., landlords, AHB, LA) via a secure one-way diode-style transmission system like LoRa TX-only, ensuring protection during transmission if they choose to do so. This summarised data is particularly useful when the sensor detects potential mould risk based on daily activities (i.e., if condensation levels persist today, mould may develop in X weeks). However, this raised concerns from stakeholders regarding governance and interference, including who will receive the reports, how these issues will be addressed, and resource allocation. SHINE's research is supported by Clúid Housing, the largest AHB in Ireland. Therefore, the initial plans leaned towards the said AHB's potential to respond to users' IAQ and IEQ needs. However, to increase users' acceptance and cooperation with this new technology, and based on their feedback, it was decided that, upon sensor deployment, users would share the data with the social housing landlords if and when they chose to.

Another way that SHINE balances power dynamics is by making complex information easily understandable to the users. The box's touchscreen features a simple design with visuals representing pollutants for comprehensibility. For example, a thermometer symbol corresponds to temperature. Moreover, the screen's simplistic and minimalistic design ensures that information is organised and not confusing. A poster or visual aid illustrating the sensor's journey, from detecting an element (i.e., CO2) to summarising the 24-hour data to transmitting it to a third party, is also available for easy comprehension of complex information, thus making scientific knowledge relatable to the locals. This visual aid can be provided during the project's future stakeholder engagement or sensor training sessions with the residents, where open dialogue will be encouraged. The recycling and proper waste disposal plans of the sensor batteries and other parts, in partnership with their housing bodies, will also be discussed during the dialogue to cultivate a sense of ownership and collaboration in the project among residents. Equipping the residents with advanced knowledge towards housing sustainability through a participatory approach helps in minimising power imbalance in the sector.

Lastly, sustaining the project's commitment to inclusive solutions, the design considered potential concerns from residents with specific needs regarding the sensor's intrusiveness. The box does not emit any sounds or lights, thus eliminating possible triggers for those with sensory impairments or schizophrenia. For those who may become paranoid or worried over frequent unnecessary alerts, we restricted notifications to once a day, when the 24-hour data is generated. Finally, the concerns of residents with general needs were also taken into account, ensuring the design is small and not an eyesore.

In summary, the technological solutions take into account data privacy and end-user challenges. These include implementing real-time monitoring to catch issues early, encouraging healthier lifestyle choices through educational programs, and utilising non-intrusive, cost-effective environmental sensors to limit disruption. Additionally, the platform created is user-friendly, simplifying complex sensor data into visual translation for users and actionable insights for the authorities responsible for interference, all while ensuring compliance with GDPR and maintaining ethical data management through transparency and informed consent.

7. Discussion and conclusions

This study shows that inclusive innovation requires constant translation between resident needs and technical design. The primary barrier to housing sustainability is the absence of participatory frameworks, not technological limitations. The stakeholder consultations conducted for the project yielded critical insights into the potential implementation of environmental sensors in Irish social housing, particularly concerning data privacy, resident participation (both general and specific needs), and the role of participatory research in shaping technological solutions.

The principal concern raised by stakeholders revolved around data privacy and management. Fears of surveillance, misuse of data (i.e., by insurance providers), and the legal implications of GDPR for landlords installing sensors in residents' homes were prominent. These anxieties align with existing literature highlighting privacy challenges associated with IoT devices and the importance of data security [35,36]. To mitigate these concerns, stakeholders emphasised the need for transparency, open dialogue, and explicit consent at every stage of the project. This aligns with Sheppard and Beck's [7] emphasis on mutual understanding and transparency for fostering stakeholder support and Ritchie et al.'s [50] call for an iterative approach that builds trust. The SHINE project's response, by designing a sensor with local data processing, limited data transmission, user control over data sharing, and transparent algorithm documentation, directly addresses these concerns and exemplifies a human-centric approach to technology design [53].

Regarding resident participation, the consultations revealed potential challenges such as residents using engagement forums primarily for complaints [49] and a potential lack of intrinsic motivation to participate if benefits are perceived to disproportionately favour landlords. Stakeholders stressed the importance of clearly articulating the personal benefits for residents (i.e., reduced repair costs, improved health), conducting pre-consultation research to understand residents' needs, and employing effective communication strategies with appropriate tone and language [54,1].

Addressing the complexities of resident participation for individuals with specific needs highlighted crucial ethical and practical considerations. Concerns about triggering paranoia in individuals with schizophrenia, sensory sensitivities in those with autism, and potential discomfort from frequent alerts underscore the need for tailored and sensitive implementation strategies. The positive experiences of vulnerable populations with technology during the COVID-19 pandemic (as noted by AHB stakeholders) offer a promising avenue for framing the SHINE sensor as a tool for improved quality of life and independent living.

The SHINE project's response to these participatory research findings demonstrates a commitment to integrating stakeholder feedback into the technological solution. The sensor's design prioritises user privacy, offers control over data sharing, simplifies complex information through visuals, and minimises potential sensory triggers. This iterative process, where stakeholder input directly shapes the technology, speaks closely with the core principles of PR [48,50] and the call for a balanced power dynamic among all stakeholders [51].

In conclusion, the stakeholder consultations provided invaluable insights that have fundamentally shaped the SHINE project's technological design and engagement strategy. By proactively addressing concerns related to data privacy and tailoring participation approaches to the diverse needs of social housing residents, the project has laid a foundation for more effective and ethical implementation of environmental sensor technology. The emphasis on transparency, user control, and clear communication directly responds to the challenges of engaging vulnerable populations in technology-driven initiatives in a way that 1) will generate perceived benefits to them and 2) allows them to have control of their own data and how it will be used. While we encountered limitations, such as the integration of our recommendations and producing accurate calculations of the sensor's economic benefits that can only eventually be done in the subsequent stages of our project, such as resident engagement before sensor piloting or sensor training sessions, the study certainly gained significant insights from stakeholders that inform ongoing and future social housing sustainability.

The key contribution of this study lies in demonstrating the critical role of PR in the early stages of developing technological solutions for

social housing. By actively involving stakeholders, residents and housing organisations can be given time and a platform to explain and understand the nature of the project, what it entails, and what advantages and disadvantages it will bring them. Thus, addressing transparency and cultivating consent for future participation in similar projects. The SHINE project has moved beyond a purely technocentric approach to one that is human-centred and contextually relevant to the Irish social housing sector.

Moving forward, further research is needed to evaluate the effectiveness of the implemented privacy safeguards and engagement strategies through testing out the sensors developed in the project. Future investigations could focus on the long-term impact of proactive maintenance informed by sensor data on residents' health and well-being, as well as the sustainability of social housing assets. For upcoming research of a similar inquiry, it is also valuable to investigate how these environmental planning frameworks can be applied in the context of Irish social housing and public governance while using digital innovations and interventions, such as the use of ISO 14,001 or green servitization models. A quantitative mixed-method approach could also expand the findings and provide a deeper level of generalisability of results. For instance, research on environmental sensors placed in Irish homes can help validate our findings, especially regarding the data collected on mould and its impact on the health and finances of residents or landlords. The SHINE project can also be used as a case study by organisations, the government, and academia for PR in the context of social housing's environmental condition, best practice for ethically implementing IoT solutions in other sectors, and how PR can be integrated into IoT designs. More explicitly, discussions on data privacy issues should include three important aspects: transparency, open dialogue, and consent. It should also include conversations with two important key stakeholders: residents with general needs and specific needs. Finally, exploring scalable policy recommendations for integrating such sensor technology into national housing strategies, especially concerning climate resilience and home energy users, will be crucial for realising the full potential of proactive environmental monitoring in promoting social and environmental justice within the housing sector.

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CRediT authorship contribution statement

Tracy Mae Ildefonso: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Data curation. **Valesca Lima:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Stephen Daniels:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Joseph Mullally:** Software, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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