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HOUSEHOLDER READINESS FOR SMART, DATA-DRIVEN PERFORMANCE MONITORING OF HOMES

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Abstract

The decarbonization of UK homes is an essential aspect of the government's net zero ambitions. However, the challenge of the design – performance gap of new homes, and the lagging performance of existing homes remain. This paper investigates smart data-driven building performance monitoring (BPM) for homes, and the drivers of householders' acceptance and adoption. The findings from a nationally representative survey affirm previous knowledge that cost, privacy and data security would drive adoption of smart BPM. More importantly, most householders would likely adopt BPM. However, such scheme should be convenient in time, effort, and cost. Implementation should be coupled with a legal framework to address system and data security and privacy concerns; householders should have control of their own data. Lastly, integrating BPM in building regulations, incentivised retrofits and renewables schemes would increase householder awareness and confidence in its value and merit as part of any net zero home strategies.

Introduction

The UK building's operational energy in 2019 accounts for 35% of the total final energy, and 38% of the total emissions for the whole construction sector (Seminara et al., 2022). There are approximately 29 million existing homes in the UK. It takes on average 50 tonnes of CO_2 to build an average UK home and direct emissions from UK homes was 64 million tonnes (Mt) CO_2 in 2017 (CCC 2019). UK homes account for around 20% of GHG emissions so decarbonising homes is vital for achieving Net Zero targets (CCC 2022a). This challenge is not unique to the UK; around 75% of the existing 210 million homes in the EU are energy inefficient, and 75%–80% will be still in use by the year 2050 (Fabbri et al., 2016). Previous studies have emphasised the need for the operational performance of buildings to underpin strategies for green building transition, advancement of low-carbon technologies and optimisation of green building policies. There is increased proliferation of research and policies emphasising the importance of post-occupancy evaluation as a necessary component of sustainable cities and net-zero homes strategies (Jiang Shu & Wang 2022). However, the scalability and wide-scale adoption of data-driven performative evidence of new and existing buildings remain limited, and the potential to enable knowledge-driven policies and practices to deliver net zero homes remain unexplored. The broad aim of this study is to investigate the opportunities to transition UK homes towards net zero through Evidence i.e. understanding the operational performance of new and existing UK homes, and Dialogue: between policy makers, stakeholders, and householders. The study is justified by CCC (2022 a & b) as follows:

1. Most people accept the need to make the necessary home improvements to achieve net zero homes. Even though concern is high, awareness of the changes homeowners should make is low.
2. People expect the government to show leadership, be consistent and take a long-term approach to policy making. The stop-start approach to initiatives in unhelpful.
3. People want clear, bespoke, reliable, and detailed information about the changes needed to their home to achieve net zero, improved energy efficiency
4. Targeted incentives at important intervention points in the homeowner cycle is essential, but this should be complimented with effective governance of new technologies (to build trust). This includes market transformation programs e.g., moving away from gas boilers, fostering the understanding of applicability and the appropriateness of technologies for the home/homeowner, and reliable service and risk models.

Thus, this paper presents an overview of pertinent regulations, standards, and methods to support building performance monitoring, as a domain of post occupancy evaluation in homes. It posits that active participation by householders and effective dialogue between policy makers and stakeholders are necessary to achieve the widescale adoption and effectiveness of any building performance monitoring strategy towards net zero homes. Therefore, headline findings from a survey of householder regarding the adoption of in-home performance monitoring are also presented.

Definitions and strategies for building performance monitoring and evaluation

Post Occupancy Evaluation (POE) is a process whereby the post-construction performance of a building is quantitatively and qualitatively investigated against the design objectives. Post occupancy evaluation (POE) and building performance evaluation (BPE) provide key insights and inform the design and construction of future buildings. Traditionally, POE has been used to establish user satisfaction alongside certain pre-set technical criteria that a new build is expected to meet. It has proven effective in exploring cause-effect relationships between technical features of the building and user experiences and needs (Kim et al., 2013; Colclough et al., 2022). The post-occupancy agenda is well-established e.g. part of the RIBA plan of work, with tangible value to housebuilders, architects, the construction industry, residents, and wider society. Still, questions remain about its practical use and efficiency (Maslova & Burgess 2022). Thus, POE continues to exist as "a scanty endeavour of research-oriented academics, rather than being an embedded practice in the building procurement process in the UK" (Durosaiye et al., 2019 p. 347).

The BS 40101:2022 defines building performance monitoring (BPM) as the gathering of quantitative and qualitative data that characterizes the performance of a building (or separate premises within a building) and the interpretation of these data to draw conclusions regarding specific performance attributes and the overall performance of the building. Building performance monitoring and evaluation (BPM/E) sits within the framework of POE. Information and knowledge derived from BPE can be used to optimise the indoor environment for the benefit of the occupants, enable informed decisions about future building design, and improve dialogue among all stakeholders including designers, contractors, facilities managers, policy makers, regulators, and users. Specifically, it is used to (RIBA 2016; Imam, Coley & Walker 2017; Maslova & Burgess 2022; Roberts et al., 2019; BS 40101:2022; Jiang, Shu & Wang 2022).:

1. Evaluate building performance and quality in design and construction.
2. Investigate and address performance gaps.
3. Monitor resource consumption: energy, water etc., climate and environmental impact during building operation and use.
4. Monitor and manage indoor environmental quality.
5. Evaluate occupant's experience and perceptions.
6. Evaluate occupancy impact on resource consumption and building performance.
7. Establish the loop of learning from previous projects, disseminate accumulated knowledge, and improve future processes and practices.
8. Inform standards and better practices and delivery of future buildings.

Coherent and integrated building codes and standards are required for BPM goals to be achieved at a useful scale. Building policies have been broadly characterised as sticks, tambourines, and carrots: Sticks in the form of codes, standards, and regulations. Carrots are aimed at incentivising better building performance through either design, process and technological certification, innovation, or curtailment practices. Whilst tambourines target occupant habits, behaviour and practise and includes education and awareness raising e.g. energy labelling (Hu et al., 2020). The UK building regulations as the stick example defines the performance benchmarks for building safety, fabric specifications, systems design including for energy and water consumptions, and CO_2 emissions. It includes methodologies and calculators such as the Water Efficiency Calculator, the Standard Assessment Procedure (SAP for domestic buildings), The Simplified Building Energy Model (SBEM for non-domestic buildings). These methodologies help to assess and compare the energy and environmental performance of dwellings and provide accurate and reliable assessments of dwellings that are needed to underpin energy and environmental policy initiatives. The Energy Performance of Buildings Directive (EPBD) aims to drive transformations towards sustainable building performance. The EPBD (EC 2018) is the current legislative and policy instrument in the EU to promote improved performance and transformation of new and existing buildings into Nearly Zero Energy Buildings (NZEBs) by 2050 (Li et al., 2019). It requires that the operational performance of buildings, and their potential for improvement is determined and communicated to the building owners. It enumerates the role of smart technologies to deliver these outcomes. Voluntary certification schemes e.g. BREEAM, LEED also serve as carrots to incentivise good practise.

In the UK, the Future Home Standard is being proposed to address four key areas: fabric-first performance requirements, primary energy, and CO_2 emissions targets as well as building systems performance requirements. However, the current and future building regulatory plans continue to overlook opportunities for lifecycle-focussed strategies including BPM to better align new-building standards, with upgrades to existing homes. The RIBA 2030 climate challenge raises this point, and defines targets for Operational energy, Embodied carbon, Potable water use and Health and wellbeing. Whilst the LETI Design guide defines bands A – D, the product, construction, use and decommissioning stages i.e. a whole life-cycle approach. Further, there is an integrated requirement for performance monitoring with the LETI guides. A model that could be followed in future regulations.

Methodologies and systems for building performance monitoring

The BS ISO 9869-1:2014 and BS EN15316 provide detailed methodological guidelines for assessing building performance at the element or systems level. The BS 40101 and EPBD provide general methodologies and indicators for performance monitoring and evaluation. The BS 40101 sets three levels of BPE which can be undertaken for individual, subset, or cohort of buildings:

1. Preliminary or Light BPE which uses essential, coarse building and user data to partially verify performance, check anomalies, or establish a baseline performance to aid improvements

2. Standard BPE which considers a wider range of parameters, more granular data, and occupant feedback for a more comprehensive review to establish performance verification, or evidence performance gaps, or inform future building or remedial work.
3. Investigative BPE which follows the processes of Preliminary, Light, or Standard BPE and undertake targeted or specific monitoring to answer specific questions, address performative concerns, or conduct further in-depth monitoring and investigation of specific performance issues.

Building monitoring and evaluation is therefore underpinned by active and passive, quantitative and qualitative data (Figure 1) undertaken in four stages: collection, processing, commissioning and use, and communication. For instance, the EPBD requires consideration of the location and orientation of the building, outdoor and indoor climate, thermal characteristics of the building, heating installation and hot water supply, air conditioning and ventilation, lighting installation, and passive solar protection systems; account for renewable energy sources, electricity generation from CHP, district heating and cooling system, and natural lighting; and to define calculated outcomes against building typologies and categories, e.g. residential and non-residential building types and use classes. The result is typically expressed numerically in kWh/m2/y as an indicator for primary energy use (Li et al., 2019; Zhang et al., 2020).

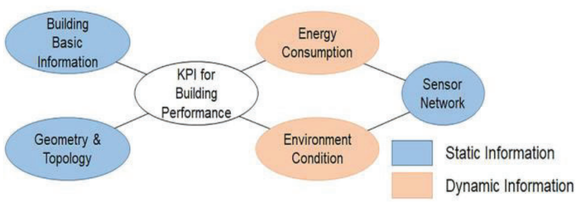

Figure 1. Information requirement for building monitoring and evaluation (Zhang et al 2020).

A smart home is a dwelling equipped with a communications network, linking sensors, domestic appliances, and devices, that can be remotely monitored, accessed, or controlled and which provide services that respond to the needs of its inhabitants (Balta-Ozkan et al., 2014). The Smart Readiness Indicators (SRI) and ratings have been introduced as an optional scheme within the EPBD. Smart readiness is the ability of a building to sense, interpret, communicate, and actively respond in an effective manner to changes in the internal and external environment, based on occupants' activities and demand, and adjust the buildings technical systems to suit (EC 2020). Smart data is derived from a monitoring network of hardware and software systems, and user feedback e.g. through activity logs, interviews, and surveys.

The current challenge with data from smart home systems includes the diversity of sources, interoperability of formats held by different providers (e.g. utility companies, IT providers) which makes the processing and effective linkage of performance data a major challenge (Tronchin, Manfren & James 2018). Within the building sector, BPM data are often stored in separate data silos: building geometry and topology information situated in the BIM file, energy consumption information stored in a sensor network or building automation platform, while environment information may come from external sources like meteorological data providers. This disparate approach to BPM has contributed to the unavailability and inaccessibility of building performance data. For BPM to be effective, these data must be linked, be understandable and communicated in the most effective format for the recipient (Zhang et al., 2020). This lack of coherence could be addressed in the short to medium term through regulatory requirements e.g. the Smart Readiness Indicator and Rating which links to the final stage.

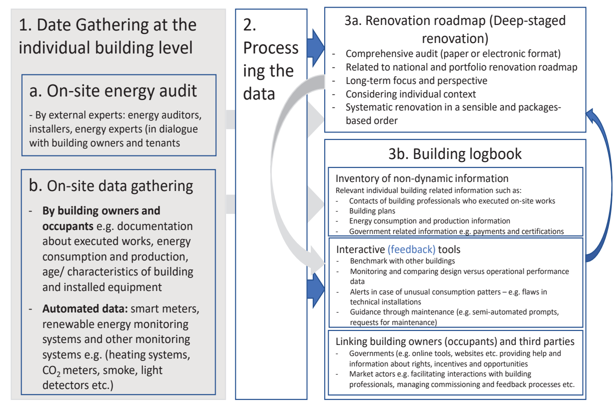

Figure 2: Building Renovation Passport – overview of its components (Source: BPIE - Fabbri, De Groote & Rapf 2016).

The final stage of BPE entails communication, raising awareness and facilitating dialogue between the key actors. Current strategies include labelling and certifications (the tambourine), typically issued to building owners and occupants, and/ or displayed. However, the efficacy of design certification schemes (BREAM, SAP etc.) and performance certification tools like the Energy Performance Certificate (EPC) to challenge and deliver post-occupancy building performance has been queried. More effective strategies like the Building Renovation Passport (Fabbri, De Groote & Rapf 2016; Figure 2) represent a new approach. The approach makes BPM and intrinsic part of a long-term (up to 15 or 20 years) step-by-step renovation roadmap for buildings. It crucially includes dialogue with building owners (based on their capacity, affordances, affordability etc). The expected benefits to owner/occupiers including reduced heating bills, comfort improvement and CO_2 reduction are a constitutive part of the approach and are explained in a user-friendly communication. The renovation roadmap can be combined with a repository of building-related information (digital logbook) detailing aspects such the energy consumption and production, executed maintenance and building plans (Fabbri, De Groote & Rapf 2016).

Summarily, the purpose of BPM/E within the POE framework is to inform transformative building regulations and standards, improve design and retrofit processes and encourage positive and sustainable experience and practices by the occupants. However, in the UK, BPM remains an ad hoc practise such that large scale longitudinal data remails unavailable, and BPM data where they exist remail in data silos (Zhang et al., 2022). This makes it inaccessible for effective decision making across the spectrum, from policy makers to householders. The wider adoption of BPE, and widespread availability and accessibility of BPE information is therefore paramount for making building performance more sustainably, and better performing new and existing homes are necessary for the transition to net zero. The review discusses the top-down policy approaches. The next steps will review householder affordance to support such strategies.

Methods

The methods applied for this study are literature review and surveys, interviews, and focus groups. The findings from this paper focusses on the outcomes of a *nationally representative* survey of UK households. At the time of the research design, the UK population was circa 67.3 million. Using the formula below, the sample size was determined as 1068 with a 3% margin of error at 95% confidence interval. Thus a target of 1000 respondents was defined: 950 online, and 50 telephone. The latter to check reliability and consistency of online survey data. The survey was deployed online during December 2022 – March 2023.

$$z2 * p(1-p)] / e2 / 1 + [z2 * p(1-p)] / e2 * N \quad (1)$$

- N is the population size
- z is the z-score
- e is the margin of error
- p is the standard of deviation

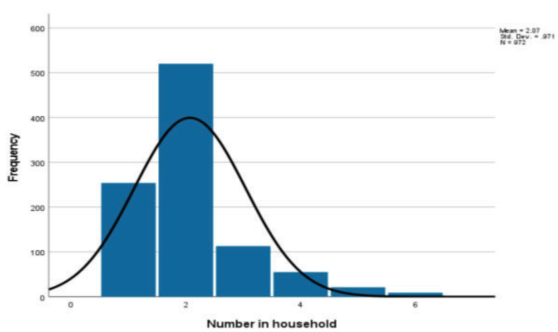

Figure 3. Number in household

A literature review e.g. Shibly et al., 2022; Lu 2021; Tamilmani et al., 2021, Shuhaiber & Mashal 2019 etc. underpinned the survey instrument design. Thus, the survey questions covered individual and household demographics, housing profile, household values and perceptions towards sustainability and technology, factors related to understanding housing quality and performance and factors informing the adoption and usage of smart technologies to support in-home performance monitoring.

Table 1. Nationally representative quota and sample

Var	Description	Target	Completes	Diff.
UK Geo	East Midlands	68	70	-2
	East of England	89	89	0
	London	125	126	-1
	Northeast England	39	39	0
	Northwest England	105	108	-3
	Southeast England	130	138	-8
	Southwest England	81	84	-3
	West Midlands	82	85	-3
	Yorkshire and the Humber	80	80	0
	Northern Ireland	25	22	3
	Scotland	79	82	-3
	Wales	47	49	-2
Age	18-24	106	103	3
	25-34	165	166	-1
	35-44	151	157	-6
	45-54	166	167	-1
	55-64	143	149	-6
	65-74	122	127	-5
	75-99	97	100	-3
	Prefer not to say	0	3	-3
Gender	Male	464	467	-3
	Female	486	492	-6
	Transgender		7	
	Non-binary		3	
	Prefer not to say		3	
Ethnicity	White / Caucasian	817	833	-16
	Asian/Asian British	68	63	5
	Black/African/Caribbean/Black British	30	29	1
	Mixed/Multiple ethnic groups	15	22	-7
	Prefer not to say		19	-19
	Other ethnic group	16	6	10
Household	1 person in household	287	254	33
	2 people in household	324	520	-196
	3 people in household	152	113	39
	4 people in household	122	55	67
	5 people in household	43	21	22
	6 people in household	14	9	5
	TOTALS	950	972	-22

The questions used the nominal e.g. categorical Yes/ No, ranked (1-10) or ordinal e.g. Likert scale units of measurement. Where relevant, open text fields were provided to collate additional opinions and viewpoints. 972 valid online survey data were received (Table 1), in the interest of space, presented in this paper. The data is skewed towards low-occupancy households (Figure 3) and efforts will be made to address this in the study's next stages. The research was approved by the relevant University ethics committee.

Findings

The house types represented in the survey are as shown in Figure 4. Housing occupancy profile was as follows: 84.1% comprised of single-family households, with the remainder lived in a shared house (7.1%), Household with lodgers (1.6%), House with multiple occupants (HMO) (2.7%), Bedsits or flatlets (1.1%), purpose-built shared amenities e.g. sheltered housing (0.5%) or temporary housing e.g. hostel/hotel/B&B (0.4%). 2.5% stated that they live in other types of housing. For housing tenure, majority 64.6% represent some form of ownership: Owner/occupier with mortgage 30.5%, owner/occupier without mortgage 32.4%, Owner/occupier shared ownership 1.7%, Others include privately rented 20.1%, Socially rented (Social housing) 6.3%, Local authority/ Housing association 7.9%, Other types 1.1%.

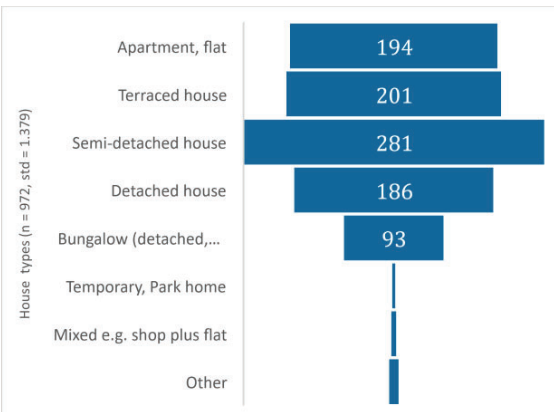

Figure 4. House types represented in the survey.

Perceptions of housing quality were mostly positive (Table 2). With a declining trend (poor or very poor) observed for parameters that impact on occupancy experience: humidity (damp and condensation issues) (31%, mean = 2.89), energy efficiency (26.1%, mean = 2.85) and sense of belonging in neighbourhood and community (25%, mean = 2.90). Open-text feedback reflected the outcome of build fabric quality (23%, mean = 3.05) mostly focussed on insulation. Additional comments gave an indication of other factors that inform perceptions of housing quality. Respondents commented on transport infrastructure and parking provisions, good and safe walking/ pedestrian routes, views from windows. An important recurring issue was air quality within and outside the home. Cleanliness and good neighbours, sense of safety and security, and being able to enjoy comfort, peace, and happiness in the home. Comfort issues included temperature, and the quality of fittings and fixtures e.g. basins, taps and showers. Some respondents commented on sustainability issues including access to recycling facilities, being able to install sustainability measures e.g. solar PV, having water meters. On the technology side, there were mentions of internet availability and connectivity so that they could for instance have “CCTV with Wi-Fi”, alluding to the sense of safety and security. Lastly, some respondents highlighted the role of landlords and management agents with comments including profiteering through maximising occupancy at the expense of space, or not investing in the quality of building systems, and condition of the dwelling.

Table 2. Perceptions of housing quality

	Very poor	Poor	Average Good	Very good
Build quality	3.8%	19.2%	45.3%	31.7%
Affordability of rent/mortgage	3.4%	13.8%	45.3%	37.6%
Energy efficient	3.9%	22.2%	59.0%	14.9%
Water efficient	1.3%	9.7%	60.7%	28.3%
Adequate amount of space for the household	2.9%	11.2%	46.0%	39.9%
The right types of spaces to suit the household	2.8%	11.7%	52.6%	32.9%
Comfortable indoor temperature (hot, cold)	3.9%	13.9%	55.3%	26.9%
Supports health and wellbeing	2.0%	11.9%	61.3%	24.8%
Amount of daylight – e.g., enough daylight from windows	1.7%	8.1%	46.9%	43.2%
Clean/ fresh air – no smells, smoke, dust etc.	1.1%	10.2%	48.5%	40.2%
Humidity problems (damp, condensation, mould)	9.0%	22.0%	40.0%	29.0%
Noise level	4.4%	14.2%	42.5%	38.9%
Range /quality of appliances	1.2%	9.3%	58.6%	30.9%
Comfort control	2.7%	11.4%	49.2%	36.7%
Level of privacy	1.9%	9.3%	49.1%	39.8%
Feeling of safety and security	1.6%	7.0%	45.8%	45.6%
Access to green space e.g., garden	4.6%	8.3%	33.8%	53.2%
Sense of belonging in the neighbourhood and community	7.1%	17.9%	53.0%	22.0%
Proximity to schools, shops, and other local services	1.3%	7.2%	40.0%	51.4%
Other	20.2%	15.7%	43.8%	20.2%

A majority of 57.7% were aware of smart home systems but do not have it. 13.2 % consider themselves to already have smart home systems, 23.8% have some awareness and only 5.3% do not know what it is. The readiness to accept and adopt smart home technologies for performance monitoring and other benefits was also explored. Majority (70.2%) indicated that cost was a key driver. Factors such as the type and age of the dwelling, level of perceived disruption and intrusiveness were considered less paramount. The comments from those who responded in the negative were interesting. Majority of this group stated that tenure (tenants, living in care homes or sheltered housing) limited their ability to make significant changes to their homes. Others stated that technical limitations such as unavailable, unreliable, or unsecure internet connectivity was an issue. Concerns about data security and privacy intrusions were expressed. Some respondents simply stated that it is part of their plan, or *I've not got round to it*". Others were not interested or do not need it: "*Machines don't know e.g. when I am warm or cold and should not dictate my life*", "*lack of interest in this tech, more trouble than it is worth*", "*not value for money, uses more electricity*", "*really don't want it, too old*", "*Partner decides on all house installations*"

Table 3. Awareness and smart home monitoring affordances

The house is too old	No	83.7%
	Yes	16.3%
The house cannot be changed to accommodate new technologies	No	84.8%
	Yes	15.2%
It will be disruptive to our home and lifestyle	No	84.4%
	Yes	15.6%
It will be expensive	No	29.8%
	Yes	70.2%
It will be too invasive e.g. I value my privacy	No	72.9%
	Yes	27.1%
Smart home affordance (Other)	No	91.4%
	Other	8.6%

Further, majority (65.3%) stated that they are willing to live in a home where smart systems are already installed for its performance monitoring before they moved in. Others would adopt if it was easy to install (71.4%), convenient to use, provides ease of control (68.1 %), secure from hacks and cyber-attacks (76%), affordable (74.9%), not intrusive on privacy (72.7%) and helps to save money (80.9%). Conversely, only 25.8% said that they will adopt it to impress family and friends, 20.7% will be influenced by others to adopt, 18.7% if promoted by the media. However, 50.9% said they would adopt smart home systems for monitoring if there was a clear message and support from the government.

There was an overwhelming preference for the implementation of smart systems for building performance monitoring to be undertaken by qualified or government certified professionals. Only 20.5% volunteered to do this themselves. Majority preferred certified tradesmen (56.3%), or other forms of government certification providers (40.8%). This was followed by building engineers (35.2%), housebuilders (30.9%), designers – architects etc. (26.7%). It was interesting that only 19.1% considered that building managers should be responsible. This reinforces the view that BPM should be implemented by those responsible for designing, renovating, or retrofitting the building.

With regards to who they trust with their BPM data, majority stated that they only trusted themselves or their household with this data (47%). Also, there was less preference for building professionals and tradesmen – 15% and 19% respectively. However, utility companies (34%) and the government – Local (28%) and Central government (26%) received more favourable responses (Figure 5). This is perhaps not surprising as utility companies already collect and utilise consumption data including for billing. There also appears to be a willingness to share BPM data with local authorities rather than centralised policy makers and regulators but this needs further exploration. Despite the affinity to support the wide scale adoption of BPM in UK homes, majority of the respondents remain sceptical about the proliferation smart home systems for performance monitoring in the short to medium term: 77% said it would take more than 10 years whilst 12% said never.

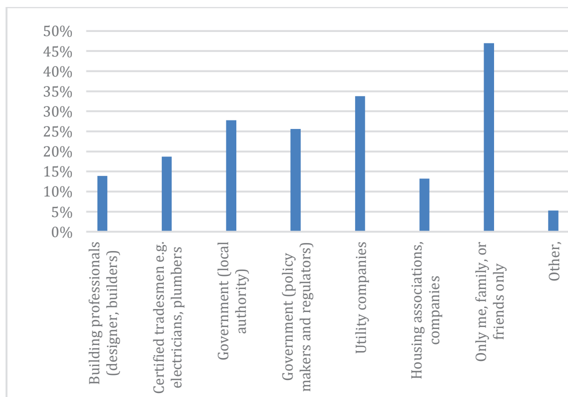

Figure 5: Trust agents for smart home BPM

Discussion

Sustainable building transformations need to occur for new and existing housing to contribute to ambitious targets to curb greenhouse gas emissions and transition to net zero homes. Due to the significant legacy of existing homes, building professionals are increasingly engaging in retrofit and renovation programs that includes improving the sustainability credentials of the building(s). Further, post-occupancy evaluation is now an essential stage in the design workflow e.g., the RIBA Plan of Work and other robust climate change readiness guidelines. The literature review affirms the efficacy of existing policies, methods, and strategies for BPM e.g. the European Smart Readiness Indicators and Rating. Shuhaiber & Mashal (2019) also forecasts that a typical family home could soon contain more than 500 smart devices. Therefore, in addition to understanding the spatial, materials and systems specifications for housing, with information tools like Building Information Modelling and others, the technical opportunity exists for building designers, engineers, builders, and managers to have access to and capitalize on the information and feedback potential of new and existing housing projects. The forthcoming Future Homes Standards also represent an opportunity to enact progressive rather than retrospective smart home BPM policy, regulations, and initiatives. This however requires building policy and regulations to be anticipatory rather reacting to technological and digital advancements.

It is necessary for policy dialogue to take place which aims to understand householder affordances and consider their concerns for the adoption of smart technologies in their homes. The findings from this UK representative household survey found that majority of the respondents would support the implementation of BPM using smart home systems. The obvious findings are that cost, privacy and data security would drive adoption. Interesting is the fact that most respondents were mostly satisfied with the quality of their homes and are not likely to adopt smart technologies for the sole purpose of home improvement. This suggests a specific propensity to adopt for the purpose of performance monitoring. However, respondents are less likely to adopt if it inconveniences them in any way e.g. through time, cost, or effort. This is demonstrated by the preference for preinstalled systems in new builds or as part of retrofit programmes. Failing this, it needs to be technically easy, simple, and affordable to install. Secondly, there needs to a facilitating environment. This includes a government certified installer scheme. Architects, architectural technologies, and other building professionals are also implicated in the positive response for implementation. This scheme should be coupled with a legal framework to address system and data security and privacy concerns. Respondents would prefer to be in control of their own data, preferring utility companies, followed by the government, over building professionals and managers to have access to this data. Lastly, incorporating BPM requirements in energy and building regulations, incentivised retrofits and renewables implementation schemes would increase householder awareness and confidence in its value and merit as part of any climate change and net zero strategies.

Conclusion

The decarbonization of UK existing homes is a necessary step in achieving the governments net zero ambitions. This study posits that a data-driven building performance monitoring (BPM) approach, and the willingness of householders to host and share the resulting data is vital for the transition to net zero homes.

The findings support two approaches for the upscaling of BPM of UK homes. First, an integrated stick, carrot, and tambourine approach to incorporating BPMs in regulations, codes, and standards to improve its widescale adoption. Secondly, that under certain conditions householders would support building performance monitoring piggy-backed on smart home systems which also provides a wide range of other benefits to the householders. Both recommendations can be implemented in an integrated manner, for example, implementing a smart readiness scheme within the building regulations for new housing or a government required Retrofit + BPM program following the example of the Renovation Passport (Fabbri, De Groote & Rapf 2016). Any scheme should consider householder implementation preferences, affordability and concerns about privacy and data security. These findings will be further explored in the next stages of this study.

Acknowledgments

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References

Balta-Ozkan, N., Boteler, B., & Amerighi, O. (2014). European smart home market development: Public views on technical and economic aspects across the United Kingdom, Germany and Italy. *Energy Research & Social Science*, 3, 65-77.

BSI (2022), BS 40101:2022. *Building performance evaluation of occupied and operational buildings (using data gathered from tests, measurements, observation and user experience)*. Specification. Published: 31 Jan 2022.

CCC (2019), *UK housing: Fit for the future?* Report by the Committee for Climate Change. Online at: https://www.theccc.org.uk/publication/uk-housing-fit-for-the-future/. Last accessed: 3 November 2022.

CCC (2022a), *Findings of a Citizens' Panel on home energy decarbonisation.* Report by the Committee for Climate Change in collaboration with the University of Lancaster. Online at: https://www.theccc.org.uk/publication/findings-of-a-citizens-panel-on-home-energy-decarbonisation-university-of-lancaster/, Published 21 September 2022, Last accessed: 3 November 2022.

CCC (2022b), *The role of deliberative public engagement in climate policy development* (University of Lancaster). Report by the Committee for Climate Change in collaboration with the University of Lancaster. Online at: https://www.theccc.org.uk/publication/the-role-of-deliberative-public-engagement-in-climate-policy-development-university-of-lancaster/, Published 21 September 2022, Last accessed: 3 November 2022.

Colclough, S., Hegarty, R. O., Murray, M., Lennon, D., Rieux, E., Colclough, M., and Kinnane, O. (2022). Post occupancy evaluation of 12 retrofit nZEB dwellings: The impact of occupants and high in-use interior temperatures on the predictive accuracy of the nZEB energy standard. *Energy and Buildings*, *254*, 111563.

Creswell, J. W., and Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Durosaiye, I.O., Hadjri, K., and Liyanage, C.L., (2019). A critique of post-occupancy evaluation in the UK. *Journal of housing and the built environment*, 34 (1), 345–352.

EC (2020), Smart Readiness of Buildings; detailing the technical modalities for the effective implementation of an optional common Union scheme for rating the smart readiness of buildings, EC 2156:2020, Online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2020.431.01.0025.01.ENG&toc=OJ:L:2020:431:TOC, Accessed: 27 March 2023.

EC (2018), European Commission Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency (Text with EEA relevance). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG, Accessed 11 January 2023.

Fabbri, M., De Groote, M., and Rapf, O. (2016). Building renovation passports: customised roadmaps towards deep renovation and better homes. Build Perform Inst Eur, 46 http://bpie.eu/wp-content/uploads/2017/01/Building-Passport-Report_2nd-edition.pdf, Accessed 06 January 2023.

Hu, S., Yan, D., Azar, E., and Guo, F. (2020). A systematic review of occupant behavior in building energy policy. *Building and Environment*, 175, 106807.

Imam S, Coley D A and Walker I (2017) The building performance gap: Are modellers literate? Building Services *Engineering Research and Technology* 38 351-75

ISO (2014), ISO 9869-1:2014. Thermal insulation — Building elements — In-situ measurement of thermal resistance and thermal transmittance,

Kim, M. J., Oh, M. W., & Kim, J. T. (2013). A method for evaluating the performance of green buildings with a focus on user experience. *Energy and buildings*, *66*, 203-210.

Li, W. (2021). The Role of Trust and Risk in Citizens' E-Government Services Adoption: A perspective of the extended UTAUT model. *Sustainability*, 13(14), 7671.

Li, Y., Kubicki, S., Guerriero, A., and Rezgui, Y. (2019). Review of building energy performance certification schemes towards future improvement. *Renewable and Sustainable Energy Reviews*, *113*, 109244.

Mahdavi, A., and Taheri, M. (2017). An ontology for building monitoring. *Journal of Building Performance Simulation*, 10(5-6), 499-508.

Maslova, S., and Burgess, G. (2022). Delivering human-centred housing: understanding the role of post-occupancy evaluation and customer feedback in traditional and innovative social housebuilding in England. *Construction Management and Economics*, 1-16.

Royal Institute of British Architects (RIBA) (2016). *Post Occupancy Evaluation and Building Performance Evaluation Primer*; RIBA: London, UK.

Roberts, C. J., Edwards, D. J., Hosseini, M. R., Mateo-Garcia, M., & Owusu-Manu, D. G. (2019). Post-occupancy evaluation: a review of literature. *Engineering, Construction and Architectural Management*.

Seminara, P., Vand, B., Sajjadian, S. M., and Tupenaite, L. (2022). Assessing and Monitoring of Building Performance by Diverse Methods. *Sustainability*, 14(3), 1242.

Shibly, H. R., Abdullah, A. B. M., and Murad, M. W. (2022). Adoption of Innovative Technology. *ERP Adoption in Organizations: The Factors in Technology Acceptance Among Employees*, 37-71.

Shuhaiber, A., & Mashal, I. (2019). Understanding users' acceptance of smart homes. *Technology in Society*, 58, 101110.

Tamilmani, K., Rana, N. P., Wamba, S. F., and Dwivedi, R. (2021). The extended Unified Theory of Acceptance and Use of Technology (UTAUT2): A systematic literature review and theory evaluation. *International Journal of Information Management*, 57, 102269.

Tronchin, L., Manfren, M., and James, P. A. (2018). Linking design and operation performance analysis through model calibration: Parametric assessment on a Passive House building. *Energy*, 165, 26-40.

York, M. (2021), *Homeowners say it's too expensive to go green,* Article in the Times Newspaper, Online at: https://www.thetimes.co.uk/article/homeowners-say-its-too-expensive-to-go-green-mhn5p2d6s, Published 01 August 2021, Last accessed: 3 November 2022.

Zhai, Y., Liu, Y., Yang, M., Long, F., and Virkki, J. (2014). A survey study of the usefulness and concerns about smart home applications from the human perspective. *Open Journal of Social Sciences*, 2(11), 119.

Zhang, Y. Y., Kang, K., Lin, J. R., Zhang, J. P., and Zhang, Y. (2020). Building information modeling–based cyber-physical platform for building performance monitoring. *International Journal of Distributed Sensor Networks*, 16(2), 1550147720908170.

Žukauskas, P., Vveinhardt, J., and Andriukaitienė, R. (2018). Philosophy and paradigm of scientific research. *Management culture and corporate social responsibility*, 121