Evaluating the effectiveness of smart home energy management systems in the real-world

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Abstract

Smart home energy management systems (SHEMS) digitally monitor, control and coordinate functions in a home for space heating, cooling, lighting, appliances, security, and renewable technologies. Although experimental trials and simulated studies on SHEMS are available, limited attention has been paid to the actual performance of SHEMS in the real-world. This paper identifies qualitative and quantitative criteria that have been used for evaluation of SHEMS in empirical studies globally from a technical and non-technical perspective. Using 14 criteria identified in the literature and grouped by the extent and type of interactions between technology and users, a new flexible and customisable evaluation framework has been developed. The framework will help to evaluate the real-world effectiveness of SHEMS in a smart and flexible energy system. It is useful for policymakers, academics, and industry to determine the success of SHEMS in delivering expected outcomes for the energy system and users.

Keywords Smart homes, smart energy management system, evaluation framework

1.0 Introduction

Several governments around the world are committed, with varying levels of obligation, to reducing greenhouse gas (GHG) emissions to net zero by differing dates, e.g., Germany and Sweden by 2045; most countries, including most in the European Union, the UK, Australia, the US. and Canada by 2050; and China and India by 2060 and 2070 respectively (1).

In 2019, the residential sector, specifically, was directly responsible for 27% of the world's electricity final consumption (2). Among selected IEA countries, space heating and cooling was responsible for 57% (space heating 53%) of total end use energy. Water heating and appliances covered 35% (appliances 19%) and the remaining 8% was from cooking, lighting and non-specified uses (3). These areas will require various approaches to reduce emissions in the domestic sector as no single technology alone can reduce global carbon emissions to respective targets. There is agreement among climate scientists that several approaches will be necessary, i.e., clean energy technology, energy efficiency, and reduction of energy demand. Behaviour (e.g. personal energy management) is significant and changes related to mobility, housing and food are all substantially important (4).

Along with low and zero carbon technology (L/ZCT), (smart) home energy management systems (HEMS/SHEMS) aim to reduce energy consumption through feedback and control by learning user patterns to enhance indoor comfort, reduce energy costs, and aid in developing demand response behaviour which can dampen peak loads reducing grid strain. An aggregate concept of a smart home management system comprises of connections and sensors that can be controlled by occupants (but can also learn to self-optimise) using remote control, computer or mobile devices that manages comfort, entertainment, security and or energy through the integration of a set of sub-systems, appliances, and L/ZCTs (5-10).

The terms 'HEMS' and 'SHEMS' are used interchangeably in the literature to describe home energy systems that are typically 'smart'[1] but not necessarily consistent in their offering. This apparent gap presents an opportunity to develop a framework for evaluating SHEMS by extracting key criteria from existing evaluation studies. Within this context, this paper aims to systematically examine high-quality studies that assess the performance of SHEMS both across the technical (energy savings, controllability, feedback, automation) and non-technical perspective (occupant experience, raising energy awareness, engagement with household energy) in the real-world. The commonly used criteria for evaluation in these real-world SHEMS studies were used to develop a detailed evaluation framework for examining the functionality and performance of SHEMS in a consistent manner with flexibility for measurement of the criteria. The following section describes the process used to select appropriate studies for the review.

2.0 Review methodology

A systematic review of the studies from 2005-2022 was conducted that omitted lab experiments and computer modelling studies. A comprehensive search of literature was performed across the interdisciplinary academic databases like Scopus, Google Scholar, IEEE-Xplore, Taylor & Francis and JSTOR, and Science Direct. To capture all eligible studies, several search terms were used using the methodology of PICO method (11-13).

These studies were further isolated to extract studies relevant for this paper based on date of publication (nothing before 2005), peer review or reputable funding bodies only, and only real-world studies were included; simulation or lab studies were excluded to capture real-world experiments with users in their home environment. The quality assessment scale in Lomas *et al.* (14) was adopted to reduce the number of studies by eliminating 'lower' quality studies according to the methodology. This scale addresses quality in two areas, reporting and research. Table 1 lists the quality assessment criteria and the scoring scale.

Query	Score
Reporting quality	
Does the author or publishing organisation have a credible track-record in the area?	0 or 1
Are the rationale and research questions clear and justified?	0, 1 or 2
Does the document acknowledge funding sources, project contributors and advisors, and list possible conflicts of interest?	0, 1 or 2
Are the methods used suitable for the aims of the study?	0 or 1
Research quality	

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[1] 'Smart' = ability to communicate and work with other networked technologies, and through this ability to allow automated or adaptive functionality as well as remote accessibility or operation from anywhere.

Has the document been peer reviewed or independently verified by one or more reputable experts?	0, 1 or 2
Do the conclusions match the data presented?	0 or 1

Table 1 – Quality assessment scale (Lomas *et al.* (14))

3.0 Review of SHEMS in literature

From the application of the quality assessment, 16 studies were considered for a deeper review. There were 13 from Europe, 2 from the USA and 1 from Asia (Japan). Two studies in the UK sampled over 1000 households / residents. Park *et al.* (15), through several field experiments of Nest smart heating control found about a 5% reduction of gas consumption; however, with several caveats and no change in user comfort. The other performed before and after trial interviews to evaluate energy savings and several qualitative aspects of smart heating controls; however, despite peer to peer reinforcement and reported improvement in thermal comfort, in this case no significant savings were found (16).

In the medium range (less than 1000 but greater than 100 households / residents in the study), there were three studies located in north Europe. The largest of these, performed a long-term study of user values in smart homes finding that security features were the most important and a touch screen display was preferred over online access through computer (17). Christensen *et al.* (18) and Nilsson *et al.* (19) found 10-15% energy savings even though several users found the displays difficult to understand.

The remaining seven European studies evaluated between 10 and 54 households each. Several of these studies, (20-24) found that when aftercare, interaction, or research related nudging ended, there was a notable reduction in user interest and engagement. As with a previous study, Smale *et al.* (21) found that the dedicated touch screen display was preferred over a web-based interface that had to be accessed via computer. van Dam *et al.* (25) studied the medium-term engagement with home energy monitors and also found that engagement did not sustain for the long-term. Portet *et al.* (26) studying elderly householders, found that they liked security functions and preferred voice control over a seemingly complex interface.

Takayama *et al.* (27), evaluating satisfaction with home automation in the USA also found a decrease in interest among users over time; however, in contrast, Woodruff *et al.* (28) found that when smart home systems are found to solve a highly personal and characteristic need then user engagement is better sustained. In Japan, Nakajima (29), found that users among 20 households were highly responsive to LED indicators which encouraged them to check energy use and reports; tips and advice were also positively welcomed by users. Finally, in a study of two households in France and Austria, user behaviour was positively influenced by energy tips (30). Overall, qualitative data on user interaction with the systems was important as all of these studies with the exception of (15) utilised questionnaires and/or interviews. All studies described are listed in table 2 with identifying characteristics and their final quality score.

No.	Ref.	Period	Location	SHEMS features	Key criteria assessed	Qualitative / quantitative data	Sample homes (H) / residents (R)	Overall quality score
1	(17)	2002-2005	Sweden	Lighting, security, climate control, hot water, large appliances, entertainment	Energy savings, indoor environment, interoperability, security, User experience, usability, Peer communication	Interview & questionnaire	365 H	9
2	(28)	2005-2006	USA	Lighting, security, large appliances, entertainment	Interoperability, security, User experience, usability, user engagement, Aftercare	Interview	20 H	8
3	(25)	2008-2009	Netherlands	Energy monitor	Energy savings, User behaviour, usability, user engagement	Interview / Meter energy data	54 R	7
4	(15)	2009-2017	UK	Climate control (heating)	Energy savings, User engagement, comfort	- / Smart meter gas data	2,448 R	8
5	(26)	2010	France	Lighting, security, climate control, hot water, large appliances, entertainment	Security, privacy, User experience, usability, user engagement	Interview	18 R	7
6	(18)	2011-2017	Denmark, Norway, Austria	Energy monitor, renewables integration, large appliance automation	Energy savings, User behaviour, user experience, user awareness, usability, user engagement	Interview	153 H	8
7	(20)	2011	Germany, Switzerland, Austria	Lighting, climate control (heating), some appliances	User awareness, usability, user engagement, comfort, Aftercare, peer communication	Interview	22 R	7

No.	Ref.	Period	Location	SHEMS features	Key criteria assessed	Qualitative / quantitative data	Sample homes (H) / residents (R)	Overall quality score
8	(27)	2011	USA	Lighting, security, climate control, entertainment, some appliances	Interoperability, security Usability, user engagement	Interview	10 H	7
9	(21)	2012-2018	Netherlands	Energy monitoring, climate control, renewables integration, large appliances	Interoperability, User behaviour, user experience, user awareness, usability, user engagement, comfort, Aftercare, peer communication	Interview	14 H	8
10	(23)	2013	UK	Lighting, security, climate control, hot water, energy monitoring	Energy savings, indoor environment, interoperability, privacy, User experience, user awareness, usability, user engagement, comfort, Aftercare	Interview / Meter energy data	10 H	9
11	(16)	2013-2014	UK	Climate control (heating)	Energy savings, User behaviour, user experience, user awareness, usability, user engagement, comfort, Peer communication	Interview / Gas meter readings	1,398 H	8
12	(31)	2017-2020	Austria, France	Energy monitoring	Energy savings, indoor environment, interoperability, security, data reliability, User behaviour, user experience, user awareness, usability, user engagement, comfort, Aftercare, peer communication	Interview	2 H	8

No.	Ref.	Period	Location	SHEMS features	Key criteria assessed	Qualitative / quantitative data	Sample homes (H) / residents (R)	Overall quality score
13	(19)	2017	Sweden	Lighting, large and small appliances, energy monitoring	Energy savings, indoor environment, interoperability, privacy, User behaviour, user awareness, usability, user engagement, comfort, Aftercare, peer communication	Interview	154 H	9
14	(22)	2018	Italy	Lighting, climate control (heating and cooling), large and small appliances	Energy savings, security, privacy, User behaviour, user awareness, usability, comfort, Aftercare	Questionnaire / Electricity bill data	10 H	8
15	(29)	2017-2018	Japan	Energy and climate monitoring	Indoor environment, User behaviour, user awareness, usability, user engagement, comfort, Aftercare	Questionnaire / Indoor/ outdoor temp., RH, indoor CO_2, particulate matter, mean radiant temp., electricity data	20 H	6
16	(24)	2018-2019	Finland	Climate control, renewable integration	Energy savings, indoor environment, interoperability, security, privacy, User behaviour, user awareness, user engagement, comfort, Aftercare	Interview / Electricity data, indoor/ outdoor temp., and RH	10 H	8

Table 2 – Summary of studies identified using the quality assessment guide

4.0 Criteria for evaluating SHEMS in literature

From the collection of literature, common motivations for the use of SHEMS have come from energy management, energy cost savings, improved quality of life, comfort, convenience, environment concerns, indoor climate control and flexibility, adaption to lifestyle, control, technical simplicity and security (32). Several users indicated more interest towards SHEMS' control over appliance usage, heating and energy management with PV systems rather than security (19, 25). Though not as frequently reviewed in studies, security features (e.g., away from home lighting and locking) were most popular with elderly users (26). All aspects of SHEMS application were usually assessed using interviews/surveys or energy consumption data with/without indoor monitoring data.

The evaluation criteria from the field studies assessed in this report were identified based on the extent and type of interaction offered between technology and users. They were grouped into three main categories because these are the primary foci of SHEMS, i.e., the various interactions between technology and the user. These were technology to technology interaction, user to technology interaction and user to user interaction.

- Technology to technology involves systems that learn from the environment without user interaction and/or provide full automation.
- User to technology interaction, involve remote management of energy and environment and user action in response to feedback via user interface.
- User to user interaction can involve feedback and support from the supplier or peer to peer communication.

Figure 1 shows the common evaluation criteria for the three interaction groups. As will be seen in the description below there was often interlinking of the three criteria.

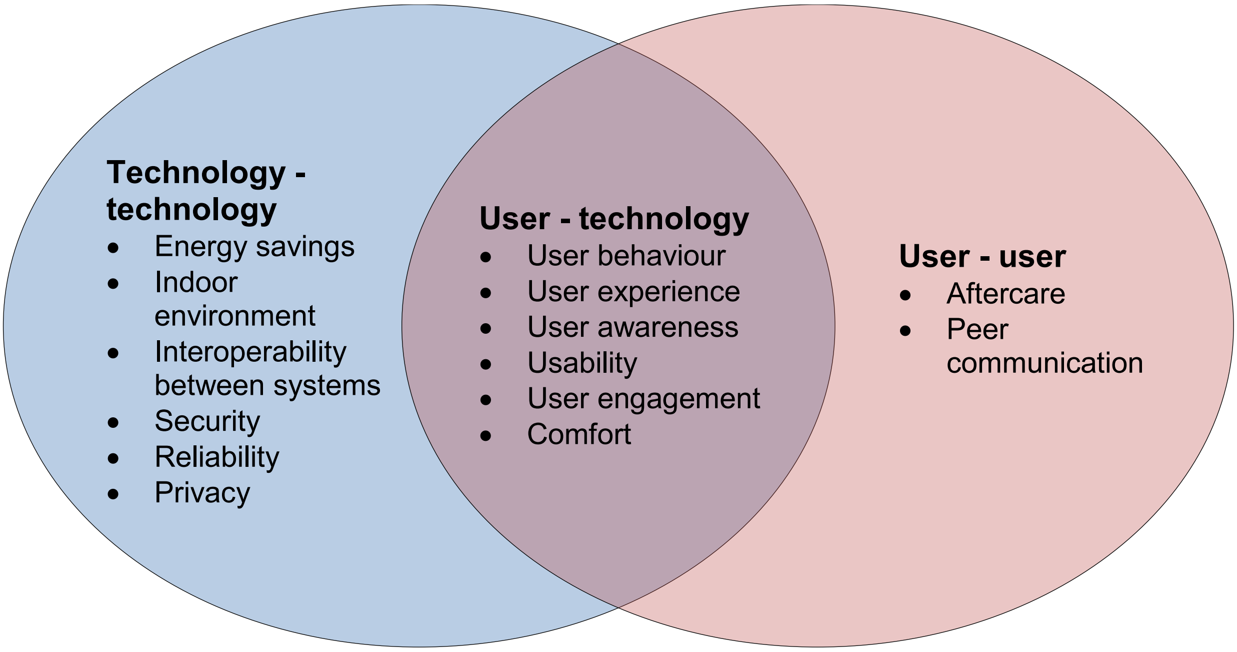

Figure 1 – Categorisation of evaluation criteria

3.1 Technology to technology interaction

Several studies (33-37) explored optimisation algorithms to control the energy flow using automation without the involvement of users to reduce energy consumption and to improve efficiency. Intrusive (installing circuit/appliance level monitoring equipment) and non-intrusive load monitoring are forms of technology driven demand side management. One study (38) used simulations of IoT-oriented SHEMS to investigate the feasibility of a fully non-intrusive load monitoring system. SHEMS have also used artificial intelligence (AI) through cloud computing to make decisions from user data. One study (39) proposed to improve customer satisfaction utilising a multi-objective optimisation model. Another set of models were investigated to optimise energy management based on uncertain human behaviours (40).

Woodruff *et al.* (28) qualitatively reviewed home automation in 20 American Orthodox Jewish households to observe the perceived benefit of home automation for religious purposes (minimising technological interaction during Sabbath). Overall, the user experience was highly satisfactory with ease of use and high tolerance for malfunctions. In this study, high user awareness among the households improved user experience. On the other hand, Hargreaves *et al.* (23) found that lower user awareness contributed to a challenging user experience, as participants found themselves struggling to improve or enhance their lives through automation. Over the long-term, the use of these systems were limited to specific user functionalities as some users prefer not to intervene with a functioning system and therefore the full potential of these systems were not realised (16, 41). Long-term user satisfaction was influenced by the robustness of the system, usability and ease of access (17).

Some users perceived smart automation technology as a convenient tool to enhance comfort in their lives. Some also expressed greater enhancement of their experience while giving full control to the system, however, this was not seen in a negative way, but a system that could adapt to their way of life (20, 28). However, some users in other studies expressed fear of losing autonomy and lack of control which caused more stress and hence preferred to have some form of control (18, 26, 41).

3.2 User to technology interaction

For SHEMS usability was heavily driven by the design (presentation/style) of the control interface. The users that did find the system easy to understand were more likely to explore, experiment, and understand their system, while users who saw the visualisations and metrics to be perplexing found themselves more disengaged in the long-term (17, 20, 26, 30, 41, 42). Van Dam *et al.* (25) found that if the user interface was highly complex to use and comprehend, the frequency of use can fade over time, reducing the energy savings. This was also validated by other studies that found non-technical users were less involved with the user interface if the data could not be interpreted accurately. It was also noted that highly complex systems and interfaces often discouraged user engagement, and most users felt negatively towards smart home technologies. When displays were not coherent, users were more dissatisfied when new settings were installed, as the familiarity over time was what kept the users engaged (18).

Responsiveness and interactivity of the interface also determined user engagement. Some users often did not want to change settings for fear of interfering with the already set system. This issue can be overcome with training sessions, trials and focus groups during installation and bringing more familiarity with their SHEMS system. The participants reported a better use of the control interface when the system was accessible through smartphones/touch screen rather than a laptop. User interaction was improved when the feedback was easily accessible from a smartphone based website, where weekly reports, peer comparison and environmental data were available (29). The inability to access SHEMS drastically reduced usability, while it was observed that leaflets, advice from installer increased usability to an extent however, with reduced interactivity over time (16).

Highly motivated participants were more likely to improve their energy savings than participants who were less inclined to care. Users who sustained their habits were found to achieve 6% savings over the long-term (25). Sustaining user behaviour was also explored by several other studies where the users were influenced by energy tips to save energy; however, too many reminders annoyed the user and that reduced user satisfaction with the system (19, 30). Alternatively, Nakajima found that the user behaviour to check up on the flashing warnings using LED indicators were highly effective, encouraging users to investigate the warning (29). Most users tended to lose patience with malfunctioning systems and thereby provide a negative review of their system (17, 19, 30, 41, 42).

Self-reported energy data, monitoring of energy and indoor environment data were collected to observe and validate the energy savings or energy reduction across several studies. Energy savings through environmental data motivated users to increase engagement, as responding to environmental prompts made them feel more energy conscious (19, 29). However, some studies reported little to no significant changes in their energy savings as they did not understand how to interpret their data or due to encountering errors in their data (17, 30, 41). When the data has errors, it becomes difficult for users to rely on the data for use in future energy savings. Data reliability as seen on the interface were important for users to take the right action to save energy (29).

3.3 User to user interaction

Studies have examined SHEMS that investigate demand response involving consumer participation, while demand side management involves the supplier providing incentives (like time of use tariff) or energy savings to encourage change in the end-user consumption (24, 43).

Frequent aftercare through support staff and feedback for any inoperable errors by the SHEMS developer greatly enhanced user experience with the operation of their systems (28). In contrast, where sufficient support was lacking from experts and developers, users were unaware of the full extent of functionalities and while suggestions ranged from feedback tips or advice from the system, it lead to a decreased user experience and awareness (28, 41). Even where some users were more engaged with the system in the case that it was a stimulating new device, this faded eventually when the experiment stopped nudging the users (e.g., providing information letters) (24).

Energy data from neighbours tend to build energy conversations, encouragement to add new devices and motivation to improve own energy savings (17, 20, 29). Weekly reports of energy consumption and peer comparison including their environmental data demonstrated an improvement in user awareness and experience (20). However, some users were naturally sceptical about the data provided on peer energy performance (19, 30).

3.4 Key evaluation criteria identified in literature

The most common study criteria across the literature were found to be usability and user engagement, followed by energy savings, user awareness and comfort (figure

2). While technology to technology and user to technology interactions accounted for more than 42% of the criteria, user to user interactions accounted for only 14% of the criteria. Technology to technology operability and user to technology interaction were most important points of evaluation, while user to user interaction was helpful in aiding the evaluation of key aspects of SHEMS. Clearly, however, many of these are strongly interlinked, e.g., usability can have a significant impact on energy savings and comfort.

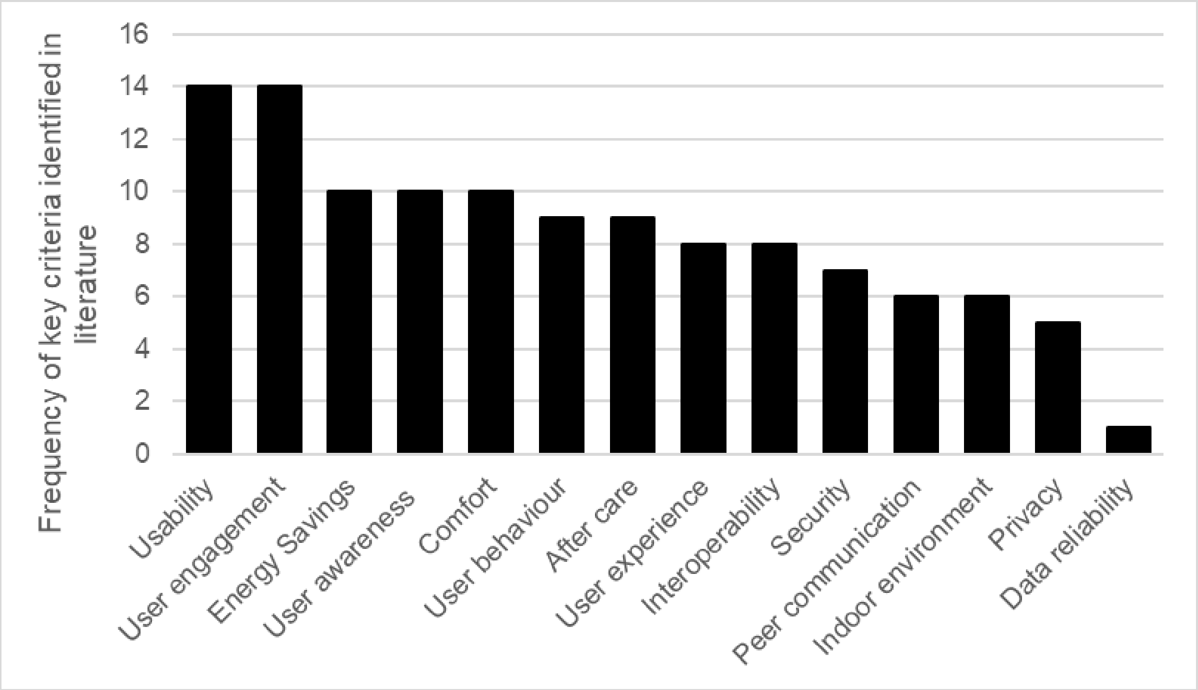

Figure 2 – Common evaluation criteria used in SHEMS studies

4.0 Evaluation framework for SHEMS

The performance criteria and critical interactions described above provides the evidence base for building a framework to evaluate SHEMS. Summarising the information from the literature reviewed, a framework for evaluation is presented in table 3. To create the evaluation framework, the criteria were described and the methods for data collection were identified. Overall, data for assessing each of the criteria can be gathered through energy assessment, indoor environmental monitoring and/or occupant feedback through surveys and interviews. The recommendations were based on the combined perspective of many users (ranging across active, passive, elderly, young, male/female and even religious groups). Therefore, this framework can be adapted more universally among various populations. Multiple approaches to adopt this framework can be developed for customisations beyond specific functionalities.

Evaluation criteria	Description	Data collection methods
Technology - technology		
Energy savings	Management and or reduction of energy consumption through smart home technologies, e.g., smart thermostat, automated load management, appliance monitoring and remote control, smart batteries, etc.	Low detail: User-reported energy meter data; smart meter data logging (non-intrusive) High detail: sub-metering: energy data loggers, appliance / plug load / lighting data monitoring
Indoor environment	Monitoring and control of the indoor environment including thermal comfort control, lighting (electrical or daylight), CO_2 or other gas monitoring, ventilation control, etc.	Low detail: Periodic temperature / RH checks High detail: temperature, RH, lux, CO_2, other gases data logging. Can be compared with window opening, shade opening, thermostat temperature setpoint / on/off settings, etc.
Interoperability	Efficient communication between systems to create a whole smart home management system.	Monitor sensors, e.g., interaction / response between such variables as external temperature, shade opening / closing, window opening / closing, and indoor temperature, etc. Questionnaire / interview may also be helpful to understand the occupant's awareness of issues.
Security	Home security measures, e.g., remote and automated lighting, door locking, window locking, alarms, etc.	Monitor interaction / response of system between occupant / stranger presence and security features; interview / questionnaire to query occupant's perception of effectiveness of security features.
Reliability	Ongoing, dependable operation of the system; no failures, data gaps.	Review data from any of the above monitoring applications; interview / questionnaire to query occupant's perception of reliability of the system(s).
Privacy	Security protection of data in the system, locally and online.	Review SHEMS provider's data security protocol, data sharing and privacy documentation.

Evaluation criteria	Description	Data collection methods
User - technology		
User behaviour	How does the user's interaction with the technology change the user's behaviour? Primarily with respect to energy consumption, appliance use, etc.	Before and after interview / questionnaire can be useful to evaluate how (e.g., energy, appliance) use behaviour is / changes.
User experience	What is the user's overall opinion of the use of the system(s)? What features stand out as helpful / unhelpful or useful / not useful?	Interview / questionnaire
User awareness	What is the user's awareness of smart systems and energy / environmental issues / aspects with respect to the features provided by the SHEMS?	Before and after interview / questionnaire can be useful to evaluate the change in awareness to smart technology, energy / environmental issues that the systems intend to address.
Usability	How usable is the SHEMS? E.g., can the user comprehend the user interface or the interconnectivity of features?	Controls survey for each point of user interface, e.g., questioning clarity of purpose, ease of access, intuitiveness, labelling / annotation understandable, ease of use, granularity of adjustments, indication of response to user request.
User engagement	Can the system maintain user commitment over the long term?	Longitudinal study via interview / questionnaire; post-study gap follow-up.
Comfort	Is the user able to change comfort perception through use of the system?	Thermal comfort surveys, thermal comfort diary. Before and after and/or longitudinal study would be beneficial.
User - user		
Aftercare	Does the producer / installer of the SHEMS provide ongoing care to ensure continuous operation, maintenance, training, or support to the user?	Review aftercare protocol and actual practice of maintenance, training and / support.
Peer communication	Social connectivity to other SHEMS users intended to encourage improved use of the systems and beneficial energy / environmental behaviour	Community focus group / workshop among multiple users; interview / questionnaire to evaluate impact of social influence / data sharing.

Table 3 – Evaluation framework for SHEMS

5.0 Discussion

From the systematic review of the 16 studies, among the three types of interactions (technology-technology, user-technology, and user-user), 14 evaluation criteria were identified. Several of these criteria were found to be interlinked. For example, user experience, user awareness and user behaviour were influenced by usability, while usability was influenced by interoperability and data visualisation which could engage or disengage users. While technology-technology criteria were assessed through the functionalities of SHEMS, user-user and user-technology was assessed through the extent of their interventions or methods used. Overall, however, for SHEMS to be a usable system, it was imperative to understand the type of users, their intentions and objectives and the context of use.

The long-term performance of SHEMS required technical features like interoperability, energy savings, security privacy and data reliability of indoor environment and energy use to be effortless and economical so that the users can experience and change their habits, increase awareness of their systems, and engage with the interface to improve their comfort. Conducting long-term interviews can aid in understanding these criteria as users can lose interest over time. User help like advice and tips by installers, from peers, or even leaflets can improve the usability and overall experience and performance of SHEMS itself and tests the flexibility of the system, which indicates the level of connectedness exists beyond just the hardware of the system for several criteria.

As several countries shift fuels to meet carbon reduction goals and or climate change and economic population shifts causes increases in electricity consumption, there is a need to manage peak loads on the grid. SHEMS can be considered helpful in managing demand response. SHEMS, including those connected to renewable systems and smart batteries, can be used to shift peak load, such as through timing large appliance use during low load times. There will; however, need to be incentives to encourage large-scale adoption such as time-of-use-tariff.

Along with smart meters, it has been and is recommended that policymakers encourage deployment of SHEMS to boost and ensure standardisation, data security and compliance of interoperability. Furthermore, there need to be incentives for builders to include SHEMS and demand side regulations will need to be modified in line with SHEMS operations. The diverse nature of evaluation criteria and methods followed across several studies called for a coalition of these methods, to extract the optimal solution in improving the real-world performance of SHEMS. The framework developed here thus maintains customisability and flexibility so it can be adapted as per resources.

Currently as there is little to no clear evidence of the real-world impact of the performance of SHEMS (18), the presented framework can aid policies by providing reliable end-use data and criteria to inform and scrutinise the effectiveness of SHEMS. SHEMS can thus have a transformative impact to reduce energy through such an informed framework, which policymakers can utilise for creating benchmark guidelines from the evaluation criteria of SHEMS.

6.0 Conclusion

This paper has systematically reviewed evaluations of smart home energy management systems spanning the last two decades. A set of 16 studies were identified through systematic review and it was observed that usability, user engagement and energy savings were the three most evaluated criteria in SHEMS studies. As effective energy management is recognised to be a necessary part of meeting carbon reduction goals, good quality data that reflect the real-time energy use of the user is imperative for each region. What is needed is a framework to guide the evaluation of smart home energy management systems and the wealth of data that they can provide, and to assist with how to use that data to improve efficiency and multiple levels of interaction. It was noted that user experience, awareness and behaviour were influenced by usability, whereas usability was influenced by the interoperability and data visualisation could either engage or disengage users depending on the long-term intervention used. Drawing on real-world performance of SHEMS through the review of qualitative and quantitative methodologies, a detailed evaluation framework was developed discerned by three critical levels of assessment criteria involving suitable interventions. Using 14 criteria covering three types of interactions, the flexible and customisable evaluation framework was developed using a three-tiered measurement approach to address data availability. Policymakers, academics, and industry can use the evaluation framework to determine the effectiveness of SHEMS in delivering expected outcomes and establish positive feedback loops.

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Acknowledgements

This study is part of the Indo-UK RESIDE project which has received funding from the Engineering and Physical Sciences Research Council (EPSRC), UK grant no: EP/R008434/1.