Building Management Systems in residential buildings: their role in energy and indoor climate resilience

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Abstract

The building sector contributes to around 39% of the global carbon emissions, and the operation of buildings, and especially residential buildings, is a large contributor. Hence tackling the efficient operation and maintenance of residential buildings is an effective way to reduce energy consumption and carbon emissions and hence contribute to climate resilience. While the operation and maintenance phases of non-residential buildings generally rely on Building Management Systems (BMS), BMS are typically absent in standard housing; instead, residents manage their own homes individually. Through a scoping literature review, this paper investigates the potential of BMS in promoting energy efficiency, indoor climate comfort and long-term resilience (e.g., managing cold periods and heatwaves), and general suitability for the residential environment. Findings show that promoting resilience in residential buildings through the implementation of BMS is not explicitly investigated in the existing literature, instead the focus is on promoting energy efficiency, innovation and climate change mitigation. Furthermore, main BMS are designed based on solely technical parameters, neglecting social and human factors. This study therefore argues for the need to adopt a human-centred design approach to include key aspects of adaptability, flexibility, equity and inclusivity in the design and implementation of BMS in residential buildings. In the end, this paper contributes key aspects for BMS to promote resilience in residential buildings.

PEER-REVIEWED ARTICLE • RESILIENCE

Keywords: building management system, home energy management system, resilience, affordability, inclusivity.

Introduction

Continuous urbanisation and consumption of natural resources, international conflicts and climate crisis, are contributing to an emergency where natural resources are limited, even lacking in the poorest countries (Oberle et al. 2019). The building sector is responsible for around 36% of global energy consumption and for about 39% of carbon emissions (Santamouris and Vasilakopoulou 2021). To mitigate the associated impacts, a radical change into a more resilient built environment is needed not only by making the residential building stock more energy efficient but the way buildings are managed (UN Environment 2018).

Building Management Systems (BMS), a control system that monitors and regulates all mechanical and electrical equipment of the building (i.e., ventilation, heating, cooling, lighting, power system, etc.), has recently seen increased popularity as an effective solution to optimise buildings' energy systems and equipment and, consequently, reducing the energy consumption through more efficient and sustainable energy management (Hossain 2019). On the other hand, the operation and maintenance (O&M) phase, the longest phase in the life cycle of the building, is of great importance as it affects building performance and occupants' health and safety (Chan 2019). It is also essential to ensure that regulatory criteria are fully met (Ighravwe and Oke 2019), user's expectations and building intended functions are fulfilled (Silva and de Brito 2019), and maintenance costs do not increase in the long term (Ali et al. 2010). In this respect, Facility Management Systems (FMS), typically confused with BMS, assist in managing operational functions of the facility and building management system based on facilities management and operational needs (Sinopoli 2010). While FMS and BMS have been used for the O&M phases of non-residential buildings, they are typically absent in standard housing; residents manage their own homes individually instead. Because of this, there is a lack of studies that focus on assessing the implementation of occupant-control systems in residential buildings. University and office buildings are the most common building types investigated in the existing literature; mainly due to the limitations on data collection, ethics approval, etc. (Park et al. 2019).

When focusing on single housing, the implementation of Home Energy Management Systems (HEMS) has increasingly grown in interest due to a fast growing smart grid sector, i.e., a modern, automated and intelligent electric grid, that enables a more efficient power delivery, use of renewable resources and storage of excess energy (Tuballa and Abundo 2016), and a more efficient energy use in residential buildings. FMS are not commonly part of residential building management and hence not included in the scope of this study. In summary HEMS, through a hardware and software combination, is a platform that enables residents to monitor and control their energy consumption as well as their use of renewable energy (Balakrishnan and Geetha 2021). HEMS does not only support residents to reduce their energy consumption and, consequently, energy bills. Smart technologies (usually also understood as "home automation systems" (Parag and Butbul 2018)) are an important component in HEMS (referred to as 'smart HEMS' in this paper) as it supports monitoring and controlling the household's energy consumption while ensuring a healthy and safe indoor environment (Alam, Reaz, and Ali 2012). Furthermore, the European Union (EU) has included the use of smart technologies in homes (i.e., "smart homes") as one of the ten pillars in the strategic investment action areas (European Commission 2015), which is seen as an essential component for the promotion of smart energy systems and cities (H. Lund et al. 2017). Projections suggest a total of 84 million smart homes by 2022 across the EU, with the UK, Germany and France leading the market (Sforza 2019). However, security and user privacy risks related to the use of home and end-users' information hinder the implementation and acceptance levels of smart technologies in residential buildings. For instance, (Jacobsson, Boldt, and Carlsson 2016), through a risk analysis of the implementation of a smart home automation system, identify 32 risks with human behaviour as one of the four main severe risks, and argue that security and privacy should be placed at the core of the design phase. Similarly, (Marikyan, Papagiannidis, and Alamanos 2019), looking at the smart home literature from the users' perspective, highlight the need for the inclusion of the user perspective in the development of smart technologies. In a context of an energy and climate crises and a fast digital transition, there is a clear need for more resilient BMS, HEMS, smart energy systems and housing in general that enable to overcome more frequent disruptions caused by energy demand peaks, heavy winter storms, heatwaves, etc. The interpretation of the term resilience may vary across different fields (Galderisi, Limongi, and Salata 2020), and it is therefore challenging to assess how resilient engineering systems are and how to improve their resilient characteristics (Hosseini, Barker, and Ramirez-Marquez 2016). Recently, Castano-Rosa et al. (2022) reported that built environment solutions to multiple crises include green and healthy, adaptable, equitable and inclusive infrastructures. Resilient infrastructures here mean the structures and facilities needed for the functioning of society, and include: the built infrastructure (e.g., physical systems, buildings), non-material infrastructures (e.g., governance, institutions, legislation), and community characteristics (e.g., values, common interests, collective actions), all of which support and empower citizens in times of crises (Cerè et al., 2017; Hassler & Kohler, 2014).

The aim of this study is to gain a better understanding about the potential of BMS and HEMS in promoting energy efficiency, indoor climate comfort (i.e., delivering a healthy indoor environment) and long-term resilience for the residential environment. Furthermore, the main drawbacks (i.e., potential disadvantages for the end user and factors hindering adoption) and advantages are discussed. Previous literature reviews have mainly focused on gathering a better understanding about the implementation of smart technologies in buildings in general (i.e., not specifically focused on residential buildings), and how smart technologies can promote energy efficiency, innovation and climate change mitigation e.g., (Balakrishnan and Geetha 2021; Gomes et al. 2022; Nanda and Panigrahi 2016; Saad al-sumaiti, Ahmed, and Salama 2014). At present there is no review that provides a better understanding of how BMS and HEMS could contribute to a more resilient residential environment, nor how the design and implementation can achieve this. Hence, this paper, through a scoping review, gathers and analyses the existing literature on BMS and HEMS implementation in residential buildings, discussing main advantages and drawbacks, and providing a better understanding about how they should be designed and implemented to promote a more resilient residential environment.

Main home energy management systems are designed based on solely technical parameters, neglecting social and human factors.

This article is structured as follows: First, methods used to collect and analyse the data are explained, followed by an overview of the main findings. Then, key condictions on how BMS and HEMS should be designed to contribute to a more resilient residential environment are dicussed, concluding with a summary and reflections for further research. Figure 1 below shows graphically the research methodology used in the article.

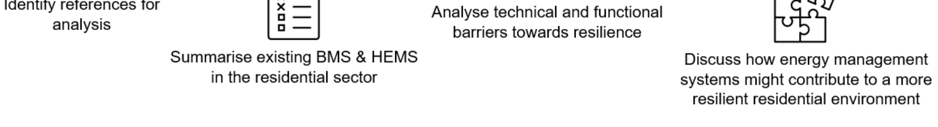


Figure 1. Research methodology.

Method

To get an overview of BMS and HEMS in housing, a scoping review was conducted, gathering main solutions implemented in the residential sector. A scoping review enables to identify, summarise and map evidence and knowledge gaps from different disciplines (Munn et al. 2018), setting the basis for a more deep investigation, e.g., a systematic literature review. The PRISMA-ScR checklist was used in this study (Tricco et al. 2018), defining three main steps: (1) searching for articles according to the inclusion criteria; (2) screening of the samples by using exclusion criteria; and (3) studying the final samples.

Figure 2 below depicts graphically the literature review protocol defined for this study. To guarantee peer-reviewed material, the source of data used was “Web of Science”. In the first step (identification), a search using the keywords ‘building’, ‘housing’, ‘energy’, ‘management’ and ‘system’ was conducted. Language was limited to English, and no year limitation was set to obtain a comprehensive understanding of the phenomena. A total of 1980 references were collected from each category (see Figure 2). In the second step (‘screening’ in Figure 2), the collection of papers was reduced to 1589 after removing duplicates, and to 893 by selecting only those references whose research focused on ‘home’, ‘dwelling’, ‘apartment’, and/or ‘flat’. Finally, because the aim was to understand the use of BMS and HEMS in the promotion of energy efficiency, indoor climate comfort and long-term resilience, papers that did not aim to improve ‘energy efficiency’, ‘indoor thermal comfort’, ‘indoor air quality’, or ‘resilience’ were excluded, resulting in a total of 58 references. The search strategy was drafted through research team discussions, in collaboration with the experienced librarian. The final search results were exported to ATLAS.ti (“ATLAS.Ti” 2022).

Regarding the data synthesis, descriptive statistics were used to analyse main paper characteristics. Qualitative data were analysed using qualitative content analysis as this method is suitable for inductive qualitative analysis and where interpretation of latent content is required (Cho and Lee 2014). The first author completed preliminary inductive open coding (i.e., bottom-up approach where codes are defined as analysis is conducted) for the characteristics of existing BMS and HEMS in the residential sector using all qualitative data, including discussion on descriptions, typologies, benefits, barriers, and recommendations. Categories for analysis were then defined, revised and refined, and scope developed. As recommended for qualitative research (Elliott, Ryan, and Hollway 2012), the first author facilitated this process by keeping a reflexive diary.

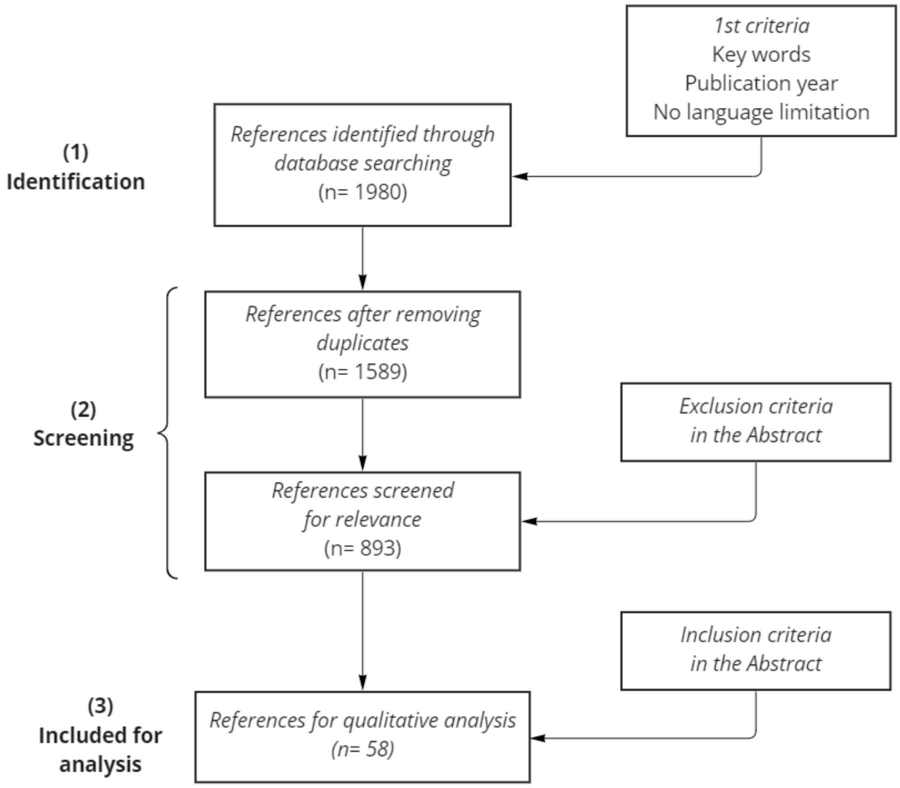


Figure 2. Scoping review protocol.

Observations and discussions

In this section, results from the scoping review are explained and discussed based on main research topics, existing BMS and HEMS implemented in residential buildings, implications and potential to promote long-term resilience. Finally, main limitations of this study are acknowledged.

Figure 3 shows graphically the chronological distribution of the reviewed literature since the first publication on the topic (implementation of BMS and HEMS in the residential sector) in 2008 until 2022. Reviewed studies were mostly conducted between 2021 and 2022 (n=30), with a special focus on investigating the implementation of BMS and HEMS in actual housing (Diba and Kristen 2021; Vakalis et al. 2021; Bai et al. 2022; Huynh et al. 2022; Ding et al. 2022), while those studies conducted before 2021 were mainly focused on developing theoretical frameworks and mock-ups, as well as their potential for implementation in actual residential cases (Zhou et al. 2016; Mirakhorli and Dong 2018; Sattarpour, Nazarpour, and Golshannavaz 2018; Khakimova et al. 2017). It is worth noting for understanding the scope of this study that further literature on the topic of BMS and HEMS implementation in residential buildings is expected in the future as a result of the fast digital transition experienced in the last decade (Papadonikolaki, Krystallis, and Morgan 2022), and this may also be implemented in the residential sector.

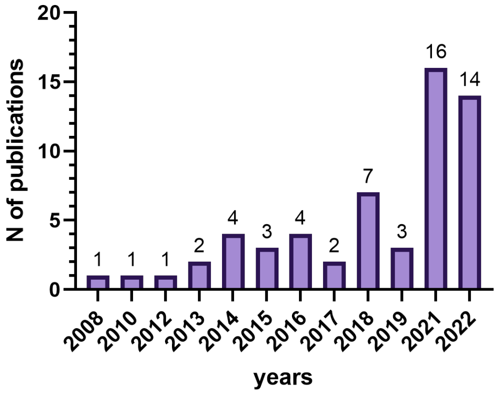


Figure 3. Graphical chronological distribution of the reviewed papers.

Through a data-driven literature review method (Park and Nagy 2018), a graphical map of the most common terms used in the reviewed literature (i.e., main research topics of the study) was created. The process consisted of searching for the keywords with at least 3 occurrences in title and abstract from the 58 references included in the scoping collection (Park and Nagy 2018). Figure 4 display a graphical summary of the most common terms used in the reviewed literature, where the larger the term, the greater the number of occurrences. In general, energy (n=87), smart (n=75), home (n=69), comfort (n=61), management, control and security (n=56), and healthcare (n=43) were the most frequently used terms in the reviewed literature.

Figure 4. Graphical summary of most common terms used in the reviewed literature (authors' own from ATLAS.ti).

The inductive open coding defined in ATLAS.ti consisted of 'BMS' and 'HEMS' as fixed terms, and 'definition', 'typologies', 'benefits', 'barriers' and 'recommendations' as variables. Results showed that the use of both terms (BMS and HEMS) is not clearly defined and then commonly mistakenly used. However, in the reviewed literature, BMS has mainly been used to refer to the use of monitoring, control and management systems in residential apartment blocks, i.e., building manager oriented solution, building functions control (e.g., movement detection for lighting, central heating system control, etc.) (Jabbour et al. 2019), while HEMS has been used when referring to individual houses; residents monitoring, controlling and managing their own energy systems, which were mainly applied in lab studies rather than real case studies (Mahapatra and Nayyar 2022).

Results from the coding analysis showed ‘energy efficiency’ (n=53), ‘indoor climate control’ (n=50), ‘control’ of energy consumption and operation (n=51), and ‘healthcare’ (n=48) as main functions and benefits of using BMS and HEMS in residential buildings, while ‘security’ (n=54), ‘cost’ (n=52), ‘technical’ characteristics (n=52), ‘accuracy’ (n=51), and ‘resident’s perception’ (n=46) as the main challenges; the five main categories identified from the literature and further explained below. Overall, the implementation of smart technologies and energy management systems were pinpointed as key solutions implemented to monitor and control the energy consumption, and for optimising (and securing) energy profiles of residents.

Existing building management systems in residential sectors

Results from the reviewed literature showed the potential of implementing BMS and HEMS in residential buildings in monitoring and controlling households’ energy consumption to reduce energy bills, while delivering healthy indoor environments. Based on the coding analysis above, five main categories were identified from the literature: (1) energy efficiency, (2) indoor climate control, (3) healthcare, (4) security, and (5) control. Below, the different categories, solutions within each category, advantages, and drawbacks (i.e., potential disadvantages for the end user and factors hindering adoption) are discussed, and graphically summarised in Figure 5.

(1.) Energy efficiency: When talking about green homes, energy efficiency refers to every aspect of energy consumption, from the source of electricity to the style of lightbulbs (Kailas, Cecchi, and Mukherjee 2013). The use of smart technology in residential buildings aims to ensure an efficient control of energy use (e.g., hot water provision) while keeping and/or increasing comfort levels; e.g., light control with no human intervention, optimal use of solar panels, etc. (Nanda and Panigrahi 2016). The four main components of HEMS used to promote housing energy efficiency can be divided into: Demand response (DR), forecasting/predicting, smart meter, and renewable energy (RE).

- *Demand response (DR),* defined as any change in household’s energy use in response to electricity price changes over time (i.e., electricity market fluctuations) or system reliability (Darby and McKenna 2012), increases energy system flexibility (e.g., balance between electricity generation and load (P. D. Lund et al. 2015)), managing the electricity use from on-peak loads to off-peak time and vice versa. DR supports consumption patterns optimisation through TOUP (time-of-use pricing), critical-peak pricing and real-time pricing (RTP); this has therefore been shown to be an effective solution to reduce household’s energy consumption and energy expenditure (Chen et al. 2018). However, main limitations identified from the reviewed literature for the implementation of DR systems are: (1) the need of energy storage systems (i.e., batteries), (2) combining the different flexibility characteristics per renewable energy source, and (3) occupants’ comfort demand, which depends on different factors, such as weather, building type, occupant age, income, acceptance rate, data protection, etc. (Behrens et al. 2018).
- *Forecasting/Predicting* households’ electricity consumption plays a key role in controlling electrical appliances and, consequently, ensuring an efficient DR system (Sianaki and Masoum 2013). These systems are mainly based on an algorithm that predicts the use of various elements of the energy systems by using weather, energy output, and expected load data collected in a database (Chen et al. 2018). However, the main limitations of these systems are the difficulty to predict electricity market

fluctuations, security-issue related, and the need of a well-stablished database and data collection network.

- *Smart meter*s' main functions are gathering automatic measurements of electricity, water, gas and/or heating consumption (both active and reactive), remote real-time monitoring and control of the dwellings' equipment (supporting decision making to meet load requirements) (Zhou et al. 2016). Additionally, smart meters enable users to monitor the energy consumption of each in-home appliance and then make optimal decisions on how to make an efficient use of each of them. However, the main limitation of the smart meters is related to security and privacy issues as data is collected in a cloud and transmitted through an online network. Most common security attacks can be divided into passive, i.e., main aim is to get information from the end users, and active, data is modified causing negative effects on the system (Alwaisi and Opoku Agyeman 2018).
- *Renewable energy (RE)* sources can reduce high peaks in the grid (including electricity market fluctuations) if combined with storage systems; the HEMS can fulfil the energy demand of the household's loads by using the grid, storage system or RE sources accordingly (Waseem et al. 2021). Most common energy sources used in the residential sector are solar (solar water heater, solar PV, solar drying and solar cooling), micro-wind, biomass (biomass combustion generation, biogas power generation), heat pumps.

(2.) Indoor thermal comfort: Indoor thermal comfort has significant impacts on occupants' wellbeing (e.g., higher risk of suffering from psychological issues), users' satisfaction and then households' energy consumption (Al horr et al. 2016). Literature showed the potential of smart technologies to ensure wellbeing and satisfaction of residents. Results from the literature showed two main components to provide thermal comfort in smart homes: (1) activity identification and (2) remote control and access (Alam, Reaz, and Ali 2012). *Activity identification* function is based on identifying user's behaviour, location, and occupancy time, requiring the use of an important number of sensors (e.g., pressure, ultrasonic for location tracking, etc.) (Huynh et al. 2022; Alam, Reaz, and Ali 2012). *Remote access and control* function enables users to control, monitor and manage access of the home environment remotely. This requires the use of specific multimedia devices (i.e., pulser meter, camera, microphone, etc.) which increases risks to occupants' privacy (Alam, Reaz, and Ali 2012; Cao 2018; Wang et al. 2021).

(3.) Healthcare: smart technologies play an important role in citizens' day-to-day activities and, consequently, have a huge potential to reduce the costs of public healthcare by supporting the provision of health care systems in homes, e.g., health insurance enrolment, rapid assistance in case of emergency, remote access to doctor appointments, etc. (Grant and Greene 2012). Local and remote monitoring are the two main systems used to promote healthcare at home according to the reviewed literature. While *local monitoring* supports health condition monitoring (i.e., ensure assistive services, report residents' health conditions, two-way communication with healthcare services, send out warnings, emergency messages and/or alarms), *remote monitoring* enables instant medical support in case of emergency; this helps elderly feel safe at home (Alam, Reaz, and Ali 2012).

(4.) Security: Literature highlighted ensuring a safe digital environment as one of the main challenges to be addressed in the implementation of smart systems at home, since user and device authentication are continuously threatened by security attacks (Jacobsson, Boldt, and Carlsson 2016). User-authentication schemes are therefore under continuous development to ensure user security and avoid security breaks (Kang et al. 2018; Alam,

Reaz, and Ali 2012; Pishva and Takeda 2006). Main solutions identified from the literature are learning-based algorithms to identify residents, perimeter intrusion control, facility access control, data access control, and fire detection (Alam, Reaz, and Ali 2012; Mahapatra and Nayyar 2022; Sooraj et al. 2020; El-Azab 2021).

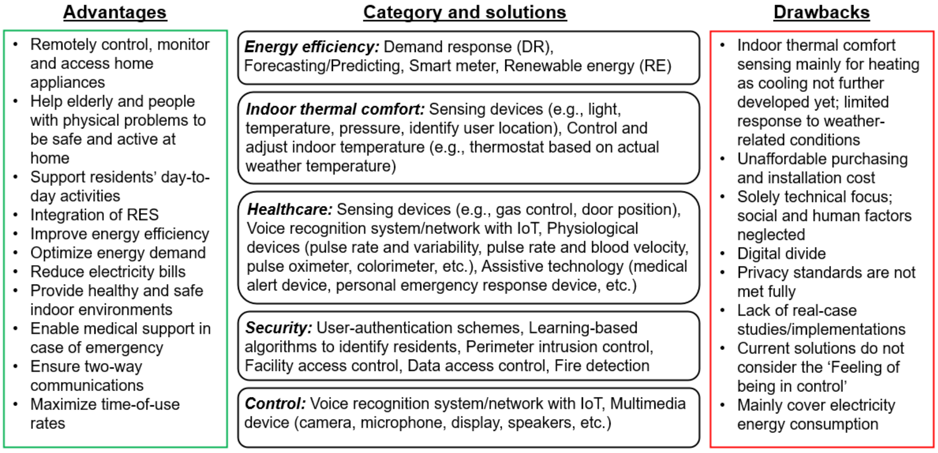
(5.) Control: From the reviewed literature, controlling the energy consumption of appliances (i.e., demand side management) to optimise its operation (e.g., switch it off during peak time) can be considered as the main function, and benefit, of current HEMS (Tascikaraoglu, Boynuegri, and Uzunoglu 2014). Three main components used to control home appliances and optimise their energy consumption are: (1) the *smart HEMS centre*, that collects all the information regarding energy consumption from the smart meters and then displays it in a user-friendly interface accessible for residents. Furthermore, smart HEMS centres can automatically define optimal appliance settings according to the resident's profile and support the management of distributed energy resources (DERs), i.e., small energy generation and storage units (D. Kim et al. 2022). (2) A set of *demand response strategies* can support residents to optimise their energy consumption based on the retail prices (price-based demand) through, for instance, time-of-use pricing (TOU), real-time pricing (RTP) and critical peak pricing (CPP), and/or based on retail electricity rate (incentive-based demand) by using programmes such as direct load control (DLC), interruptible load (IL), emergency demand response (EDR), demand side bidding (DSB), and capacity/ancillary service program (CASP) (Asadinejad and Tomsovic 2017). (3) The *communication network* that connects all the sensors and appliances with the smart HEMS centre and smart meter. This network also supports the delivery of warning messages (e.g., high temperature in specific rooms, gas leakage, etc.) and/or emergency notifications (e.g., older adult falls at home and requests of assistance, health issues in determined patients such as high blood pressure, etc.) (Ransing and Rajput 2015). Furthermore, it is important to note that two main appliance classifications are established in the literature depending on the possibility to be switched off: *controllable* appliances are those that can be switched on/off at any time (e.g., washing machine, dishwasher, water heater), while *non-controllable* appliances cannot be switched off nor planned in scheduling time because of continuous working operation (such as refrigerator, lighting) (Tascikaraoglu, Boynuegri, and Uzunoglu 2014).

Overall, the literature review found that the use of smart energy systems and technologies in the residential sector (i.e., BMS and HEMS) has a huge potential to improve (1) *energy efficiency* (e.g., supporting the integration of RE as well as an efficient use of electricity and demand response, reducing electricity bills, energy demand, and environmental impacts (Balakrishnan and Geetha 2021); (2) *indoor thermal comfort* (by maximizing time-of-use rates); (3) *healthcare* (e.g., assisting users' day-to-day activities and, consequently, more sustainable built environment (D. Kim et al. 2022)); (4) *security*; and (5) *control* (e.g., by ensuring two-way communications -smart system and residents and vice versa- and mitigating grid stress without significant investments (Aliabadi et al. 2021)). Furthermore, BMS and HEMS can increase consumers' awareness about their energy consumption, motivating (as well as empowering) them to have a more positive behaviour towards energy conservation; moving from passive to active actors in the energy management system (Mahapatra and Nayyar 2022).
However, several challenges were found in the literature that hinder an effective and broad implementation of BMS and HEMS in the residential sector, and these are as follows:

- Cost: Purchasing and installation costs are still too high, meaning that they are not affordable for all citizens, and vulnerable groups in particular.

- *Technical*: Global priority is put in developing smart HEMS towards a more sustainable and reliable (green) energy supply for smart grids, with special attention to the technical aspect, but social and human factors are neglected. This technical focus leads existing solutions to be too technical and difficult to use by most citizens, as it requires them to have basic digital knowledge, jeopardising equity and inclusivity, and triggering a potential digital divide. In this scenario, users' individual needs and expectations (for current and changing lifestyles) are overlooked, increasing users' rejection rates. Thus, smart BMS and HEMS must be co-created through a human-centred approach to ensure that they are low-threshold and accessible for all people (e.g., including elderly).
- *Security*: Privacy standards have not been fairly considered in the development of existing smart HEMS solutions, which makes privacy matters an important limitation for the design of residential appliance control systems (Mirakhorli and Dong 2018). For instance, collection of occupancy presence data and lack of verification of the observed behaviour in the data from the smart meters are very limited, and then problematic to be used, due to limited access to the home after the smart solutions have been implemented (Mirakhorli and Dong 2018).
- *Accuracy*: The number of simultaneous occupants in the house is an important limitation for either the sensing system (i.e., most systems are defined to track one or two people maximum) or the availability of all of them to use the HEMS (meaning not all end users have basic knowledge to use the system). This limitation makes it difficult for the smart HEMS to define optimal demand response strategies (Gomes et al. 2022). The reviewed literature showed that, due to the difficulties to access homes, get ethics approval, interact with the end user, the implementation of smart HEMS in real-case studies in housing are limited, and then mainly conducted in labs or particular scenarios under controlled conditions.
- *Resident's perception*: The 'feeling of being in control' from the end user is an important factor to be considered during the design and implementation process of smart HEMS, as residents want to feel like they can change the indoor conditions if needed; an essential factor to ensure high residents' acceptance rates. This feeling of being in control is often called users' 'uncertain behaviours' because they are not possible to predict based on the smart residential energy hub (SREH), which collects energy demands from smart meters and price signals (Lu et al. 2020).

Figure 5 below provides a graphical summary of the main categories targeted in the reviewed literature and most common BMS and HEMS solutions implemented in residential buildings, listing the main advantages (on the left side) and drawbacks (on the right side).



Advantages

- Remotely control, monitor and access home appliances
- Help elderly and people with physical problems to be safe and active at home
- Support residents' day-to-day activities
- Integration of RES
- Improve energy efficiency
- Optimize energy demand
- Reduce electricity bills
- Provide healthy and safe indoor environments
- Enable medical support in case of emergency
- Ensure two-way communications
- Maximize time-of-use rates

Category and solutions

Energy efficiency: Demand response (DR), Forecasting/Predicting, Smart meter, Renewable energy (RE)

Indoor thermal comfort: Sensing devices (e.g., light, temperature, pressure, identify user location), Control and adjust indoor temperature (e.g., thermostat based on actual weather temperature)

Healthcare: Sensing devices (e.g., gas control, door position), Voice recognition system/network with IoT, Physiological devices (pulse rate and variability, pulse rate and blood velocity, pulse oximeter, colorimeter, etc.), Assistive technology (medical alert device, personal emergency response device, etc.)

Security: User-authentication schemes, Learning-based algorithms to identify residents, Perimeter intrusion control, Facility access control, Data access control, Fire detection

Control: Voice recognition system/network with IoT, Multimedia device (camera, microphone, display, speakers, etc.)

Drawbacks

- Indoor thermal comfort sensing mainly for heating as cooling not further developed yet; limited response to weather-related conditions
- Unaffordable purchasing and installation cost
- Solely technical focus; social and human factors neglected
- Digital divide
- Privacy standards are not met fully
- Lack of real-case studies/implementations
- Current solutions do not consider the 'Feeling of being in control'
- Mainly cover electricity energy consumption

Figure 5. Graphical summary of main categories targeted in the reviewed literature with most common BMS and HEMS solutions in residential buildings. Main advantages are listed in the left side and drawbacks in the right side (Authors' own contribution).

Potential for resilience in residential buildings

As explained above, results from the reviewed literature (58 references were screened) showed the potential of implementing smart BMS and HEMS (particularly alongside the use of smart technology and networks) in monitoring and controlling households' energy consumption to reduce the energy bills, while delivering healthy indoor thermal comfort. However, the concept of 'resilience' and how to promote long-term resilience in the residential sector through the use of smart BMS and HEMS is not investigated (explicitly discussed) in the reviewed literature. In this respect, there is a need to understand how smart BMS and HEMS need to be designed and implemented to enhance resilience in the residential sector and our society in general. (Castaño-Rosa et al. 2022) created an evaluation framework of key characteristics for resilient solutions to multiple crises impacts to support the implementation of resilient solutions in the built environment, promoting the main resilience attributes (i.e., agility, restorative, preparedness, adaptability, robustness, and participatory). These key characteristics can be summarised as the implementation of a bottom-up and top-down approach to create a well-coordinated system, definition of systematic communication across different stakeholders, allocation of emergency resources, promotion of social capital, and inclusion of citizens into the decision-making process. Thus, this evaluation framework was used to investigate and discuss the conditions for smart BMS and HEMS to promote resilience in residential buildings.

There is the need to adopt a human-centred design and control approach to include key aspects of adaptability, flexibility, equity and inclusivity in the design and implementation of smart home energy systems in housings.

Literature showed the potential of smart BMS and HEMS to improve ***preparedness*** attributes of the housing energy system, i.e., capacity to plan ahead and prepare for unknown impacts, just before the disturbance event happens (Tong 2021). DR and forecasting/predicting features can support the end user to respond to unexpected disruptions in a timely manner by establishing priorities for actions, for instance, estimating the probability of disruptions and then defining time-of-use rates for primary/non-controllable and secondary/controllable equipment. Additionally, resources provision is a key characteristic of a resilient housing energy system, i.e., defining a back-up system to maintain security and health functions as well as systems performance (Samsuddin et al. 2018). The back-up system can be provided by a smart energy storage system, which can be in the manner of heat (hot water tanks) or electricity (via batteries) (Büyük, Avşar, and İnci 2022). The capacity to prepare ahead can also help enhance the ***robustness*** attributes, i.e., the smart BMS and HEMS have the capacity to prevent or mitigate the severity of the associated impacts during short or long-term shocks (Lak, Hasankhan, and Garakani 2020). Similarly, the more prepared the whole system is, the better the ability of residents to overcome different disruptions with the lowest impact possible during the disturbance events in a timely manner. For instance, adopting alternative energy resources during outage or electricity market fluctuations (e.g., use of RE), mobilizing resources according to users' needs – related to the ***agility*** attribute (Nik and Moazami 2021; Shafiei Dastjerdi et al. 2021). Furthermore, data gathering and quick analysis functions play an important role in the ***adaptability*** attribute, as it can promote the ability of smart BMS and HEMS to quickly readjust itself and then support on decision-making to implement optimal changes/solutions after the disruptions (Cerè, Rezgui, and Zhao 2017). Thus, it is clear from the reviewed literature that flexibility of the power system (control production and/or consumption of electricity according to different variables), the physical indoor environment (occupants' capability to adapt to different circumstances), and real-time energy monitoring and diagnostics (with a well-stablished database, network and AI technology) are some of the main features for smart BMS and HEMS to promote resilience (H. Kim et al. 2021). A strong adaptability attribute may at the same time enhance the ***restorative*** attribute, which is the capacity of the smart BMS and HEMS to recover its initial functions and performance, helping residents in the recovering process (e.g., make decisions, take action effectively, ask for healthcare, receive medical emergency assistance), after disturbance events (Ouyang 2017; Francis and Bekera 2014).

Finally, findings highlighted the need to follow a ***participatory*** approach when designing and implementing smart BMS and HEMS in residential buildings. In this study, implementing a participatory approach entails the promotion of decision-making through community engagement, enhancing the ability to collaboratively find an optimal solution, i.e., residents as an active actor rather than passive in the design and implementation process (Shafiei Dastjerdi et al. 2021). This way, the needs of all the different residents can be met fully, linking to the ***inclusiveness*** attribute, during and after the disturbance, e.g., helping elderly and people with physical problems to feel safe and be active in the home environment (Sharifi 2016).

However, analysing the main drawbacks identified from the reviewed literature (see Figure 5), it is clear that existing smart BMS and HEMS solutions implemented in residential buildings have not been designed based on occupants' needs and expectations but solely focused on technical parameters. This means that they aim to meet specific thresholds and/or standards instead of users' needs. For instance, purchasing and installation costs are not affordable, and social and human factors are neglected increasing the risk of a digital divide. Similarly, potential security issues and the lack of 'feeling of being in control' are not well addressed. There is therefore a clear need for further understanding users' interactions with the indoor environment, and how to optimally develop and implement smart BMS and HEMS to overcome main (social) drawbacks, e.g., complexity, reliability, privacy and security, etc. (Balta-Ozkan et al. 2013). This paper suggests that this can be achieved through a human-centred design approach where users' perspectives are included at the design phase and assessed after its implementation to ensure that solutions perform as expected (Agee et al. 2021). Human-centred design can be defined as an approach to systems design and development in which, through an iterative process, the users are involved in the whole process, understanding their needs, activities and environment (Giacomin 2014). This approach helps develop interactive systems more usable, equitable, inclusive, adaptable and flexible according to the users' needs. There are different human-centred design approaches (e.g., empathic design, contextual design, co-design, participatory design, ethnography, user-led approach). It is always important to reflect on the best approach for each situation depending on the two tensions that can appear (i.e., (1) within the design team, or (2) between the design team and users (Steen 2011). It is also important to note that a key component to consider is the possibility to gather users' experiences after the implementation of the technologies, and not just to codesign at the start. This will help to assess the acceptance rate and whether the technologies are performing as expected. However, as highlighted in the introduction section, there is little research on assessing the end-use efficiency of smart BMS and HEMS in residential buildings, mainly due to the difficulties to access the residents after the commission. Hence user acceptance evaluations typically capture users' experiences in labs or single-occupant apartments, missing out therefore on the complexities of real home life environments where practices are shared and negotiated between residents and their visitors (Darby 2018).

To overcome these limitations and mitigate the performance gap, using the *domestication framework* (i.e., processes to describe and analyse the acceptance, rejection and use of technologies by considering the diversity and complexity of everyday routines, dynamics and rules) has been shown as an effective tool (Juntunen 2014). The success of this framework relies on presenting the technologies as useful, reliable and trustworthy tools, implementing three specific learning stages: (1) users learn about the technology and what it can offer (cognitive learning); (2) then they learn how to use it (practical learning); and (3) finally they learn about the meaning of the technology, what are the benefits and why they should use it (symbolic learning) (Hargreaves, Wilson, and Hauxwell-Baldwin 2018). In the end, households need to be part of the whole process (design, implementation, and use), and therefore designers and architects play an important role in a successful implementation of smart BMS and HEMS. Clearly, housing and technology design must be aligned with each other as well as the users' needs, solving current mismatches in which housing may not be suitable for new technologies and vice versa (Altomonte, Rutherford, and Wilson 2015).

Figure 6 below depicts graphically the key components for smart BMS and HEMS to promote a more resilient residential building, where users' needs are included in the whole design process through a human-centred design and control approach. Thus, smart BMS and HEMS can promote energy efficiency, provide a healthy and safe indoor environment mitigating the impact of a changing climate and electricity market, while contributing to an equitable, inclusive, adaptable and flexible residential environment; currently overlooked in the reviewed literature.

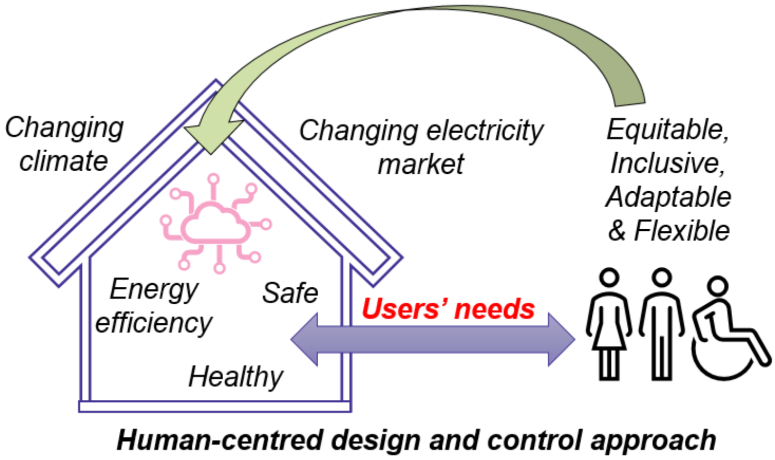


Figure 6. Graphical summary of key aspects for smart BMS and HEMS to enhance resilience in residential buildings.

Limitations

The literature collection was carefully screened and analysed. However, the research term selection may have left some relevant publications out of the analysis, as only publications investigating smart energy management systems in the residential sector were included, as well as different search term combinations could have been used. Only peer-reviewed articles and proceedings were included. Furthermore, the analysis was conducted emphasising energy efficiency, indoor climate comfort and resilience, thus, other aspects may be excluded. Finally, it is worth highlighting that newly published literatures on the topic of smart BMS and/or HEMS published since the time of scoping review (September 2022) have not been included.

Conclusions

This article, through a scoping review on BMS and HEMS in residential buildings, provides a better understanding about the potential of BMS and HEMS in promoting energy efficiency, healthy indoor environments and long-term resilience for the residential sector, discussing main advantages and drawbacks. Results from the reviewed literature show that, though there has been a significant growing interest in the last few years, the implementation of smart BMS and HEMS in residential buildings is relatively limited; mainly implemented in a small scale and/or under controlled lab conditions. Furthermore, although the use of both terms BMS and HEMS is not clearly defined; results show that BMS mainly refers to the use of monitoring, control and management systems in residential apartment blocks while HEMS refers to individual houses. There are still very limited applications in real case studies.

Findings highlighted that smart technologies and energy management systems are mainly used to monitor and control the energy consumption, and optimising (and securing) energy profiles of residents. Key solutions can be divided into *Energy efficiency* (mainly focused on DR and use of RE); *Indoor thermal comfort* (covering sensing devices, control and adjust indoor temperature); *Healthcare* (through sensing devices, voice recognition system/network with IoT, physiological devices); *Security* (with user-authentication schemes, learning-based algorithms to identify residents, data access control); and *Control* (by voice recognition system/network with IoT, multimedia device).

Regarding the main drawbacks of using smart BMS and HEMS in residential buildings identified from the reviewed literature, those are listed as follows:

- Social and human factors (i.e., user’s needs) are not considered in the design nor implementation, leading existing solutions to not be designed with users in mind, neither inclusion of vulnerable groups, such as e.g., elderly. This fact jeopardises a just digital transition and increases the digital divide.
- Aspects such as users’ safety and security are still under development.
- Most of the solutions included in the reviewed literature are based on theoretical models and/or solutions tested in labs, with limited applications in real case studies.
- Lack of reliability and confidence from the end users to use smart devices, e.g., fear of not being in control of their home.
- Not easy-to-use as it always requires basic knowledge from the end user (i.e., solely technical focused design with too many technical features, which scares people and increases rejection).
- New technologies are expensive and not affordable for most citizens (vulnerable groups in particular). Furthermore, there is a lack of financial support for first purchasing to make it accessible.

To overcome existing drawbacks and promote resilience, this research suggests that solutions must be *equitable and inclusive*, meaning that they are (1) designed to meet the need of most vulnerable groups (i.e., easy-to-use for elderly or people with impairments); (2) affordable for all social groups (i.e., currently purchase costs do not make them affordable and accessible for low-income people, which is a key characteristic for housing resilience); and (3) empower (vulnerable) people by supporting their day-to-day tasks and addressing climatic and social challenges. Furthermore, solutions must enable *adaptability* and *flexibility*, covering (1) the end users' needs eventually (i.e., different people, pets, etc.); (2) a changing climate (to predict outdoor temperatures -heatwave, heavy rainfall, etc.); (3) a changing society (ensuring reliability and security without jeopardising people's privacy and safety); and (4) considering real-time changes or disturbances.

In conclusion, the main contribution of this study is providing a better understanding about existing smart BMS and HEMS solutions implemented in residential buildings, highlighting that both smart BMS and HEMS need to be designed through a human-centred and control approach to promote a more resilient built environment. Currently, technological solutions are designed to solely meet technical criteria without considering the whole design cycle and placing the end user at the last stage, which makes it difficult to achieve a successful implementation in general. This paper argues for the need to design technological systems *with* the end user (*human-centred design and control approach*), instead of *for* them (*final product*) to promote a more resilient residential sector. Thus, future practices in the field and practical policy decisions must be strengthened in this line.

Acknowledgements

Authors acknowledge the INPERSO -Industrialised and Personalised Renovation for Sustainable Societies - Horizon Europe funded project (number 101069820) and the Academy of Finland mobility funded project DIGI4GREEN – Intelligent monitoring, digital operation and maintenance of green buildings towards carbon-neutral societies (number 350105).

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