CRITICAL FACTORS FOR THE ADOPTION OF SMART HOMES FOR ENERGY EFFICIENCY

IMPLICATIONS FOR CONSUMERS AND PROVIDERS

APPENDIX

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This document is the Appendix for the report: "Critical factors for the adoption of smart homes for energy efficiency: Implications for consumers and providers", published by National Energy Action (NEA), Newcastle University, Northern Gas Networks and Northern Powergrid.

A. Methodology

The review was a stream-based systematic one producing robust and reliable results that synthesise and map the knowledge related to the data and digital technologies for smart-home energy management. In order to ensure that the findings were reached in a reliable and valid manner the study followed a three-stage approach, as proposed by Tranfield [72] namely: planning the review, conducting the review by analysing papers and reporting emerging themes and recommendations.

The planning stage of the review included the preliminary survey of the literature in order to develop and refine the review protocols. A meeting was arranged to discuss the high-level strategy that the two teams would need to follow. The criteria were refined by having follow-up meetings between members of each team and between the two teams. This made it possible to agree on the strategy to follow and the implementation steps for operationalising the review.

The next step was to develop the protocol for the review, which included the search criteria, the papers selected for the review and the method of conducting the analysis used in the next stage. The preliminary stage of the review involved a discussion among the members of the review teams to establish the research protocol. We then formulated the exact review question and this facilitated the decision on the inclusion criteria. We expected to cover the relevant sources published in academic and industry journals and project reports over the past decade. We reviewed the abstract of each retrieved source to assess its relevance. Only documents that found agreement from the majority of the review members would be included for analysis.

The themes identified guided the qualitative review, which was undertaken by each team. The discussion of each of the themes aimed to present the academic and industry perspectives, prioritising factors of importance and discussing the relationships among them. This made it possible to create a framework for understanding the technology adoption when it comes to smart-home technologies applied to energy management.

Academic Literature

The conducting stage of the review involved a systematic search, based on relevant search terms. The electronic database Scopus was selected as it represents the largest database of citations and abstracts of the research literature and provided a wide coverage of the review topic [32]. The key word selection revolved around the term "*smart home*". The term 'energy' was not used in the first instance in order to ensure that an inclusive approach was adopted. The open search resulted in a data set of 15,878 documents. These were filtered using the provided search options. An advanced search option was enabled that limited results to document types in the form of "articles" and "reviews" published in the English language. A restriction of the search criteria to papers published between 2015 to 2022 was applied. This time frame promised a comprehensive coverage of the smart home development and adoption by users. Additional filtering was applied based on the subject areas. These included computer science, engineering, energy, material sciences, social sciences, business and management, etc. As a document can belong to multiple subject areas, we excluded areas such as physics and astronomy, biology, mathematics, chemistry, chemical engineering, earth sciences etc. This resulted in 2826 papers. Finally, we filtered documents based on keywords that were related to energy such as energy management, energy efficiency, energy management systems, energy conservation, electric power utilization, heating etc. Similarly, we excluded keywords that were not deemed sufficiently relevant, e.g. Low Power Electronics, Network Architecture, Stochastic Systems etc. This resulted in a set of 167 papers. Meta-information about these papers was exported for review by the academic team. The academic panel members reviewed the keywords, titles and abstracts of all the downloaded documents to determine the selection of articles for the review. Panel members scored papers based on their potential relevance. Members of the team ranked the papers as 2=relevant, 1=potentially relevant, 0=not relevant. A total of 70 articles were selected.

SCOPUS SEARCH STRING

TITLE-ABS-KEY ("smart homes") AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "DECI") OR LIMIT-TO (SUBJAREA , "HEAL") OR LIMIT-TO (SUBJAREA , "ARTS") OR LIMIT-TO (SUBJAREA , "PSYC") OR LIMIT-TO (SUBJAREA , "NURS") OR LIMIT-TO (SUBJAREA , "ECON") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "MULT") OR EXCLUDE (SUBJAREA , "IMMU")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (EXACTKEYWORD , "Energy Utilization") OR LIMIT-TO (EXACTKEYWORD , "Energy Management") OR LIMIT-TO (EXACTKEYWORD , "Energy Efficiency") OR LIMIT-TO (EXACTKEYWORD , "Energy Management Systems") OR LIMIT-TO (EXACTKEYWORD , "Energy Conservation") OR LIMIT-TO (EXACTKEYWORD , "Home Energy Management Systems") OR LIMIT-TO (EXACTKEYWORD , "Electric Power Utilization") OR LIMIT-TO (EXACTKEYWORD , "Renewable Energy Resources") OR LIMIT-TO (EXACTKEYWORD , "Electric Utilities") OR LIMIT-TO (EXACTKEYWORD , "Energy Resources") OR LIMIT-TO (EXACTKEYWORD , "Home Energy Managements") OR LIMIT-TO (EXACTKEYWORD , "Energy") OR LIMIT-TO (EXACTKEYWORD , "Home Energy Management System") OR LIMIT-TO (EXACTKEYWORD , "Electric Batteries") OR LIMIT-TO (EXACTKEYWORD , "Electric Energy Storage") OR LIMIT-TO (EXACTKEYWORD , "Energy Storage") OR LIMIT-TO (EXACTKEYWORD , "Home Energy Management") OR LIMIT-TO (EXACTKEYWORD , "Heating") OR EXCLUDE (EXACTKEYWORD , "Smart Power Grids") OR EXCLUDE (EXACTKEYWORD , "Electric Power Transmission Networks") OR EXCLUDE (EXACTKEYWORD , "Smart Grid") OR EXCLUDE (EXACTKEYWORD , "Scheduling") OR EXCLUDE (EXACTKEYWORD , "Optimization") OR EXCLUDE (EXACTKEYWORD , "Demand Response") OR EXCLUDE (EXACTKEYWORD , "Integer Programming") OR EXCLUDE (EXACTKEYWORD , "Wireless Sensor Networks") OR EXCLUDE (EXACTKEYWORD , "Sensor Nodes") OR EXCLUDE (EXACTKEYWORD , "Forecasting") OR EXCLUDE (EXACTKEYWORD , "Photovoltaic Cells") OR EXCLUDE (EXACTKEYWORD , "Stochastic Systems") OR EXCLUDE (EXACTKEYWORD , "Deep Learning") OR EXCLUDE (EXACTKEYWORD , "Genetic Algorithms") OR EXCLUDE (EXACTKEYWORD , "Multiobjective Optimization") OR EXCLUDE (EXACTKEYWORD , "Peak To Average Ratios") OR EXCLUDE (EXACTKEYWORD , "Big Data") OR EXCLUDE (EXACTKEYWORD , "Learning Algorithms") OR EXCLUDE (EXACTKEYWORD , "Network Architecture") OR EXCLUDE (EXACTKEYWORD , "Particle Swarm Optimization (PSO)") OR EXCLUDE (EXACTKEYWORD , "Embedded Systems") OR EXCLUDE (EXACTKEYWORD , "Fuzzy Logic") OR EXCLUDE (EXACTKEYWORD , "Green Computing") OR EXCLUDE (EXACTKEYWORD , "Mixed Integer Linear Programming") OR EXCLUDE (EXACTKEYWORD , "Algorithm") OR EXCLUDE (EXACTKEYWORD , "Appliance Scheduling") OR EXCLUDE (EXACTKEYWORD , "Dynamic Programming") OR EXCLUDE (EXACTKEYWORD , "Microgrids") OR EXCLUDE (EXACTKEYWORD , "Neural Networks") OR EXCLUDE (EXACTKEYWORD , "Optimization Algorithms") OR EXCLUDE (EXACTKEYWORD , "Real Time Systems") OR EXCLUDE (EXACTKEYWORD , "Scheduling Algorithms") OR EXCLUDE (EXACTKEYWORD , "Secondary Batteries") OR EXCLUDE (EXACTKEYWORD , "Uncertainty Analysis") OR EXCLUDE (EXACTKEYWORD , "Low Power Electronics") OR EXCLUDE (EXACTKEYWORD , "Power Management (telecommunication)") OR EXCLUDE (EXACTKEYWORD , "Power Markets") OR EXCLUDE (EXACTKEYWORD , "Distributed Computer Systems") OR EXCLUDE (EXACTKEYWORD , "Electric Power System Control") OR EXCLUDE (EXACTKEYWORD , "Electric Vehicles") OR EXCLUDE (EXACTKEYWORD , "Gateways (computer Networks)") OR EXCLUDE (EXACTKEYWORD , "Nonintrusive Load Monitoring") OR EXCLUDE (EXACTKEYWORD , "Optimal Scheduling") OR EXCLUDE (EXACTKEYWORD , "Smart Cities") OR EXCLUDE (EXACTKEYWORD , "Advanced Metering Infrastructures") OR EXCLUDE (EXACTKEYWORD , "Data Handling") OR EXCLUDE (EXACTKEYWORD , "Iterative Methods") OR EXCLUDE (EXACTKEYWORD , "Markov Processes") OR EXCLUDE (EXACTKEYWORD , "Model Predictive Control") OR EXCLUDE (EXACTKEYWORD , "Optimisations") OR EXCLUDE (EXACTKEYWORD , "Wireless Sensor Network") OR EXCLUDE (EXACTKEYWORD , "Computer Circuits") OR EXCLUDE (EXACTKEYWORD , "Electric Load Dispatching"))

Industry and Policy Literature

Prior to the call for evidence (CfE) being issued and the review being undertaken, key search terms and inclusion/exclusion criteria were agreed upon. This was developed through several discussions between the core review team and informed by additional feedback gathered with project partners.

As there is no single database used to conduct the review of the industry and policy-based based literature – often referred to as grey literature - a broader strategy for searching for relevant publications was deployed. The evidence review included publications and resources that had a primary focus on the following:

- *smart homes*
- *smart technology*
- *adoption (enablers/barriers)*
- *water and/or energy*

Reports and resources were also included where there was a secondary focus in any of the following additional areas:

- *water efficiency*
- *water poverty*
- *energy efficiency*
- *energy poverty*
- *water/energy related vulnerability/ies*
- *consumer behaviours and behaviour change*

The inclusion criteria for all resources and reports were as follows:

- Non-academic grey and industry or policy-based literature
- Published/produced since 2012
- Published/produced in English
- Focused primarily but not exclusively on the UK context (to ensure focus on UK policy, housing conditions, climate, etc.)

The conducting stage of the review of the industry and policy literature has involved a cross-sectoral CfE, which was issued to a range of relevant stakeholders and partners. The CfE was distributed to established networks and contacts via associated mailing lists, direct emails, social media accounts, and word-of-mouth in workshops and at other relevant events. Alongside this, the industry and policy literature review team undertook a rapid evidence review of publicly available online resources, including reports, consultation responses, evaluation documents, regulatory guidelines and related publications, and to a lesser extent, also considered news articles, blog posts, and other media publications where such resources were deemed highly relevant.

A total of 13 responses to the CfE were received from representatives of industry, government, the charitable sector, and academic institutions, who provided a combined total of 104 resources. The team further identified 184 resources. The range of resources from the NEA-led evidence review and the CfE included policy and Government reports and strategy documents, evaluation reports of services and schemes, evidence reviews, White Papers, industry good-practice guides, presentations, web and news articles, blog posts, among others. Following this, a sort and sift exercise of the initial 288 resources was completed by the NEA team to identify those resources of highest relevance to the overarching aims of the project. This involved reading executive summaries where found, reviewing contents pages, and searching documents for relevant text. In doing this, a consideration of key factors such as the technologies, demographic groups, geographical focus, policy context, and user groups, among other factors, were considered in terms of approaching the assessment of the available resources. A total of 69 resources were included in the final review.

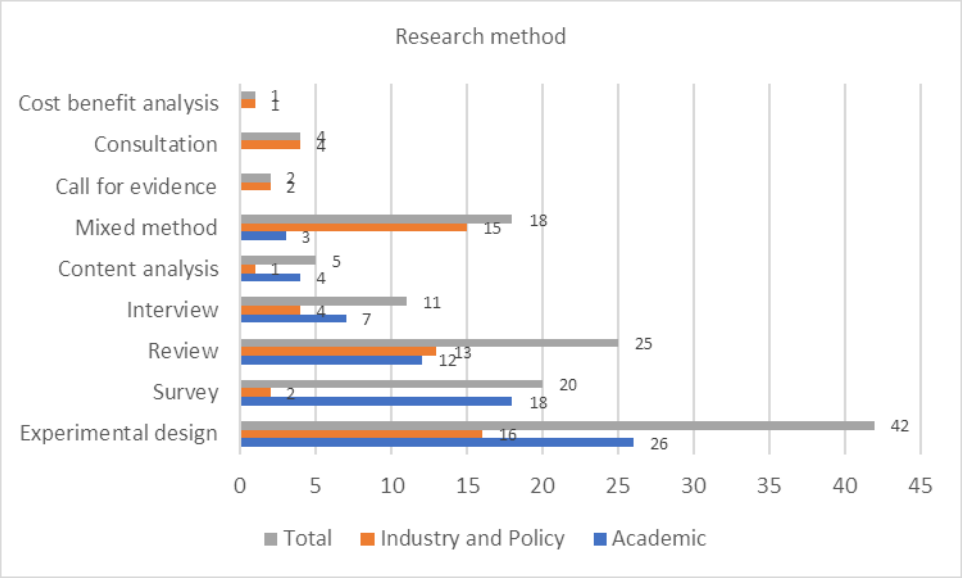
B. The literature covered

This section briefly describes the key characteristics of the literature analysed in the review. Due to the divergent nature of the academic literature and the industry and policy literature, some key characteristics are common to all the literature reviewed, some are present only in the academic literature, and some are present only in the industry and policy literature. For this reason, this section is split into four subsections, covering: a) key characteristics common to all the literature, b) key characteristics of the academic literature, and c) key characteristics of the industry and policy literature, and d) the technologies characterised as related to Smart Homes in all the literature.

Key characteristics of all the reviewed literature

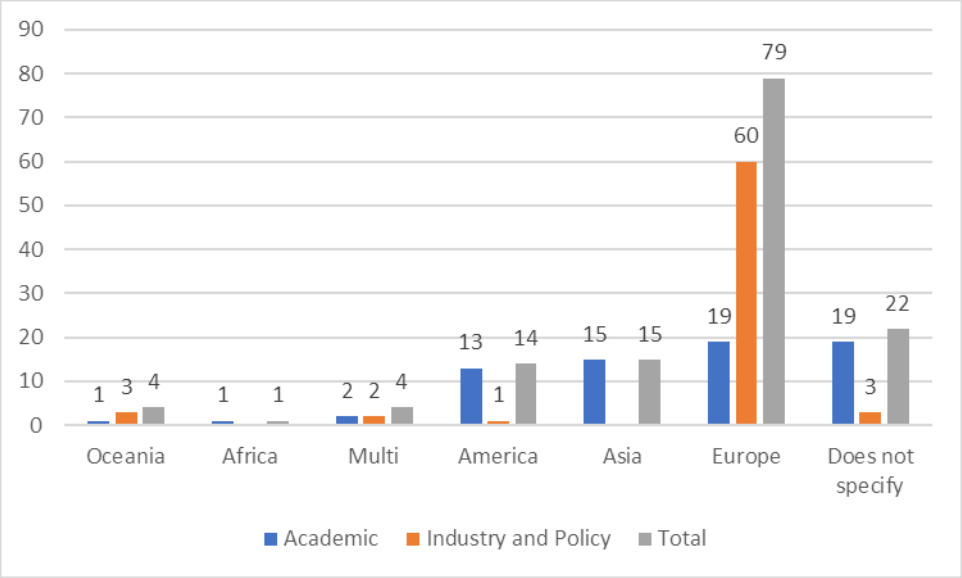
Based on the systematic literature review, research methods utilised in existing works related to Smart Homes are identified (Figure 1). As Figure 1 shows, in both the academic and industry and policy literature, existing works related to Smart Homes are most likely to involve an experimental design. In the academic literature, this involves laboratory work and testing about the planning, development, and energy testing of technologies associated with Smart Homes. Similarly, in the industry and policy literature, this involves studies testing or trialling new Smart Home technologies in different contexts. Other research methods identified in current works are survey, review, interview, content analysis, and mixed methods with 20, 25, 11, 5, and 18 works, respectively. Mixed methods studies, particularly those involving qualitative (e.g. interview, research diary) and quantitative (e.g. questionnaire) methods alongside other methods, were more frequent in the industry and policy literature (n=15). Three methods were identified as unique to the industry and policy literature: calls for evidence, consultations, and cost benefit analyses, with 2, 4, and 1 works respectively.

Figure 1: Research Methods Utilised by the Reviewed Articles



Europe (n=79) was the most studied area, followed by Asia (n=15) and America (n=14). However, there was variation between the academic and industry and policy literature. The majority of industry and policy works identified were from a European context (n=60), which reflects the methodology utilised (as described in Section 2.2. above). In contrast, there was a balance of works identified by the academic review in America (n=13), Asia (n=15), and Europe (n=19). The most prevalent two countries in Europe were the UK and Germany. In the industry and policy literature, many works focused on more limited geographical areas, such as 1one of the devolved nations of the UK (England, Scotland, Wales, Northern Ireland), or a specific place or region (e.g. Aberdeenshire, London). Finally, multiple continents (n=4) on four occasions were included in the study. However, many papers did not provide information that could help us note where the research took place, primarily in the academic literature (n=22).

Figure 2: Continent

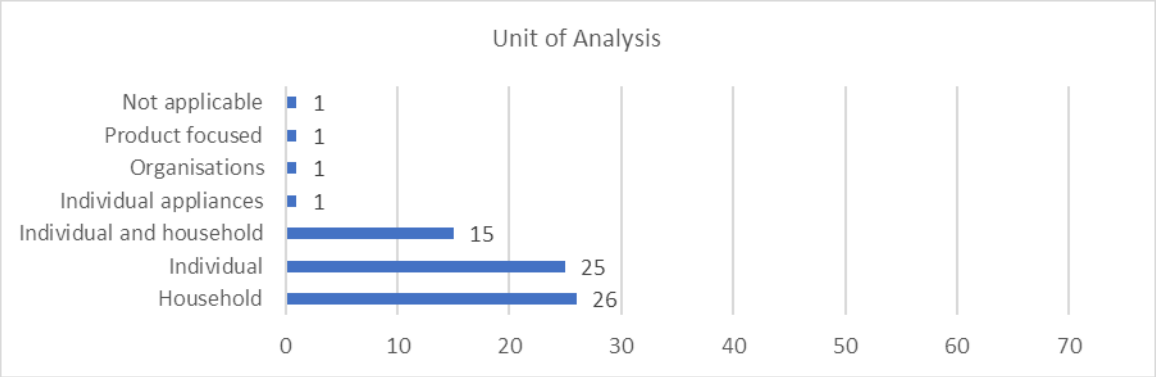


Research was conducted on either an individual (n=25), group/household (n=26) level or both (n=15) levels (Figure 5). Understanding behaviours on an individual level enables us to notice the specific motives a person has that are not connected to or influenced by the group. Understanding behaviours on a group and household level enables us to realise the ultimate impact the consumption is having on an aggregate level, regardless of the nuances of individual level behaviour. Thus, optimally, understanding both is necessary and less well studied.

Academic review

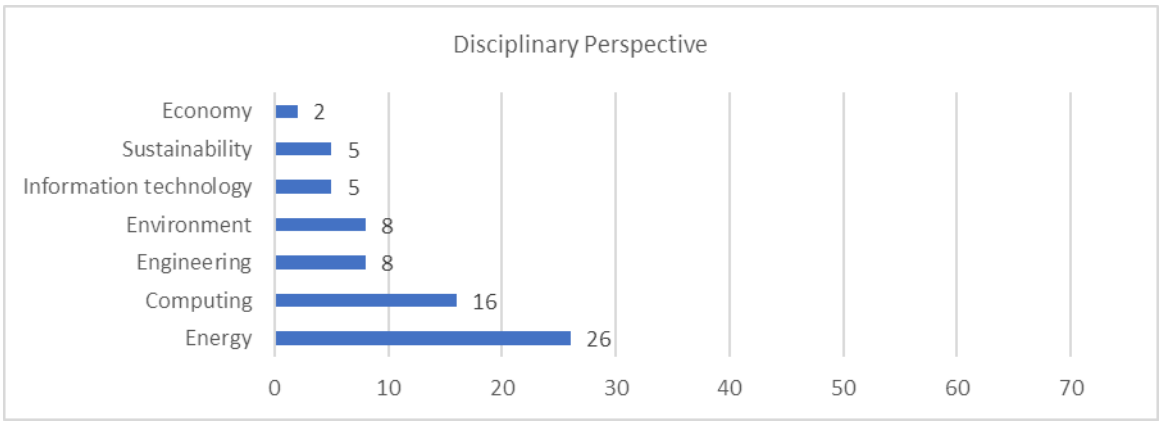
In the academic literature, research was conducted on either an individual (n=25), group/household (n=26) level or both (n=15) levels (Figure 3). The industry and policy literature focused on similar units of analysis but with significant differences, so this is considered independently in Section 3.3.

Figure 3: Unit of Analysis - Individual/Household



The academic literature review conducted was able to identify existing works' disciplinary perspectives (Figure 4). Based on the analysed review, most of the existing works related to smart homes, revolving around the energy disciplinary perspective. On the other hand, research works associated with smart homes from the economic disciplinary perspective are found to be the least common. Computing, engineering, information technology, and sustainability are other disciplinary perspectives of the reviewed articles.

Figure 4: Disciplinary Perspective

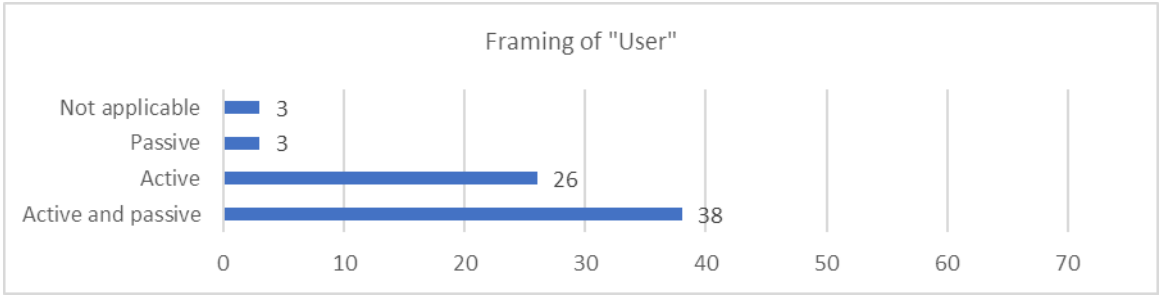


These are the five stages of adoption (Figure 5) according to diffusion of innovation theory. Awareness: A person becomes aware of the innovation. They have some idea of what it is, and what it does. Persuasion: A person develops an attitude towards the innovation, a favourable or unfavourable one. They are compelled to seek information about the innovation. Decision: A person weighs the pros and cons of making use of the innovation. They decide to adopt or reject it. Implementation: A person puts the innovation to use. At this stage they are still determining how useful it is. Continuation: A person checks the results of the innovation decision. They come to a final decision on whether to keep using the innovation. This decision may be motivated by group confirmation (interpersonal factors).

Figure 5: Stage of Innovation and stages covered in reviewed papers (in brackets are number of stages covered)

Users can be defined as a person who uses or operates something, in this case smart technologies. Users can be categorised as passive (n=3), active users only (n=26), and both (n=38) (Figure 6). A passive user is affected by the technology but does not engage with this intentionally. An active user is a person who engages in the smart technology intentionally. Finally, some papers did not state this as relevant (n=3).

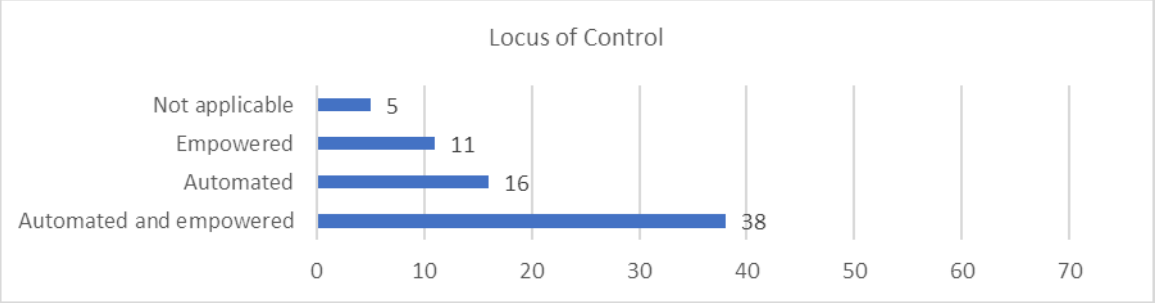
Figure 6 Framing of "User"



Locus of control is defined as the degree to which people believe that they, as opposed to external forces (beyond their influence), have control over the outcome when interacting with the smart technologies. The locus of control of users can be categorised as empowered (n=11), automated (n=16), or both (n=38). An empowered user is someone who feels that they have the strength, confidence, tools, and resources to control their

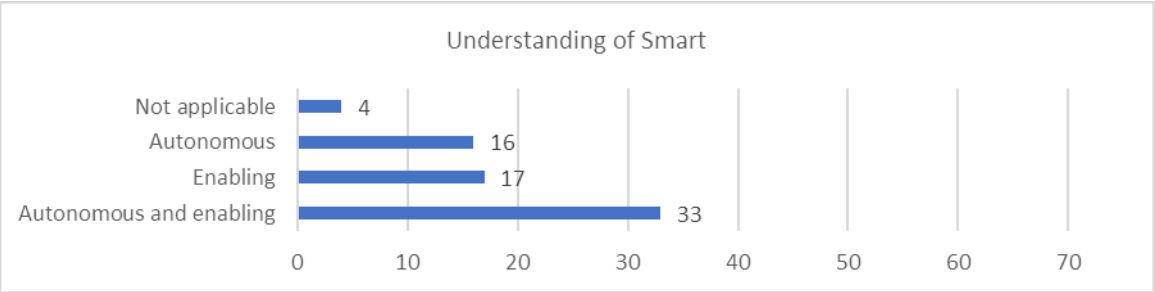
smart technologies. Automated, not empowered, users are people that believe that external forces (beyond their influence) have control over the outcome of the smart technologies. Finally, some papers did not state this as relevant (n=5).

Figure 7: Locus of Control



'Smart' (of a device) is defined as a technology that can be programmed so as to be capable of some independent action (Wilson et al., 2017). Smart can be categorised as autonomous (n=16), enabling (n=17), or both (n=33) (Figure 8). Smart meaning autonomous means that the technology is capable of operating without direct human control. Smart meaning enabling means that the technology gives (someone) the authority or means to do something that affects how the technology operates. The combined condition means that technologies act without direct control of a human as well as benefit from the human authority affecting how the technology operates.

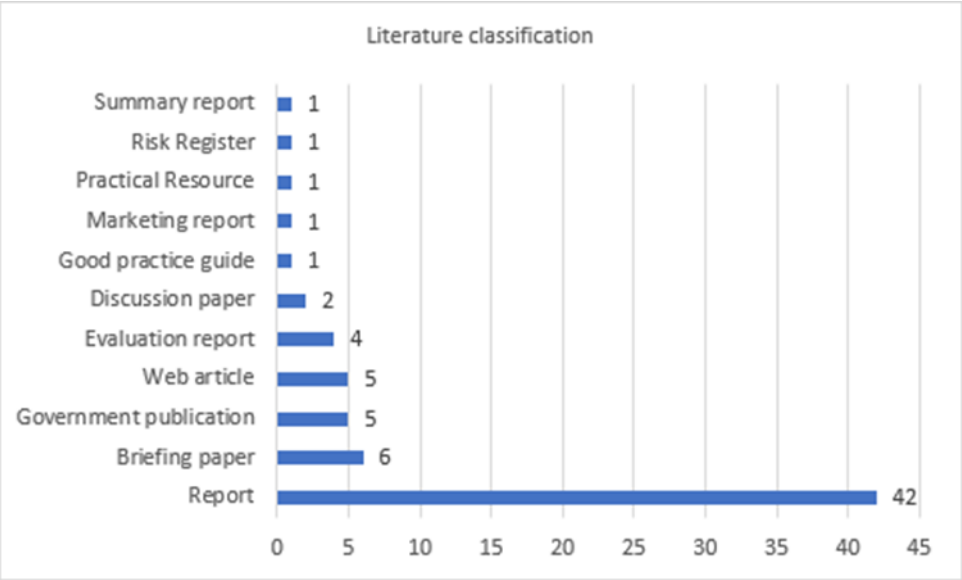
Figure 8: Understanding of "Smart"



Industry and policy literature

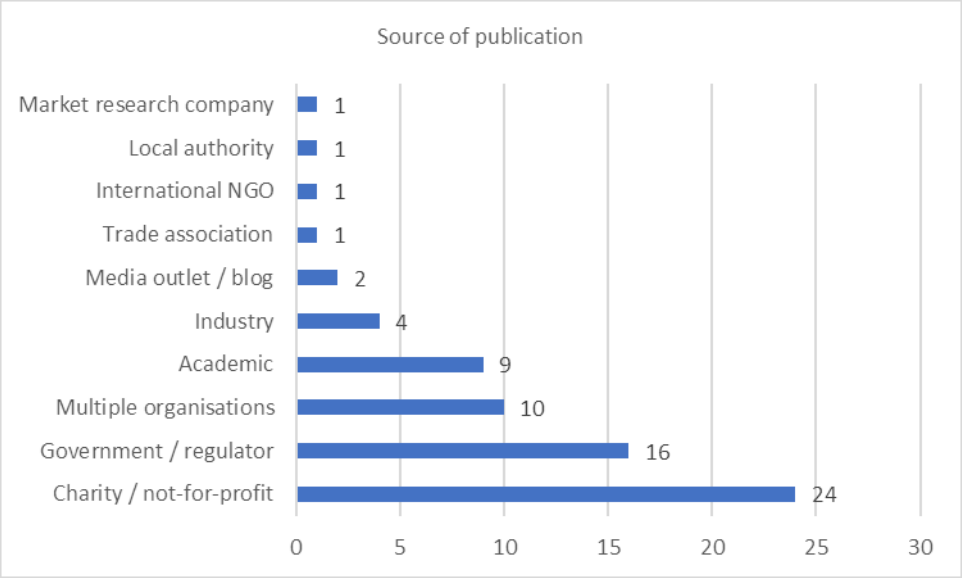
In the industry and policy literature, the majority of studies examined can be classified as reports that described the analysis and results of a particular piece of research or work (n=42) (Figure 9). Other reports were distinguished as evaluation reports, the outcome of an evaluation of a scheme undertaken by an organisation (n=4), a marketing report, based explicitly on market research (n=1), and a summary report, which summarised the outcomes of a project for which a more detailed report of findings was not available (n=1). Other literature identified included briefing papers, which provided summaries and assessments of a particular topic, but which were not based on any distinct research (n=6), government publications, primarily by the UK government and/or energy regulators (n=5), web articles (n=5), and discussion papers (n=2).

Figure 9: Classification of industry and policy literature



In terms of the source of publication for the industry and policy literature, Figure 10 shows that studies published by charities and not-for-profit organisations were the most prominent (n=24). Studies published by governments and/or regulators, primarily authored by or commissioned by the UK government and energy regulator, were also prominent (n=16). 10 studies were classified as having multiple sources of publication because they were authored and published as a result of collaborations between different organisations (e.g. charities, industry actors, academics). 9 studies were classified as based on academic research, but not published in peer-reviewed academic journals (e.g. reports of academic research projects for wider audiences). Other studies were identified as published by industry (n=4), media outlets / blogs (n=2), trade associations (n=1), international NGOs (n=1), local authorities (n=1), and market research companies (n=1).

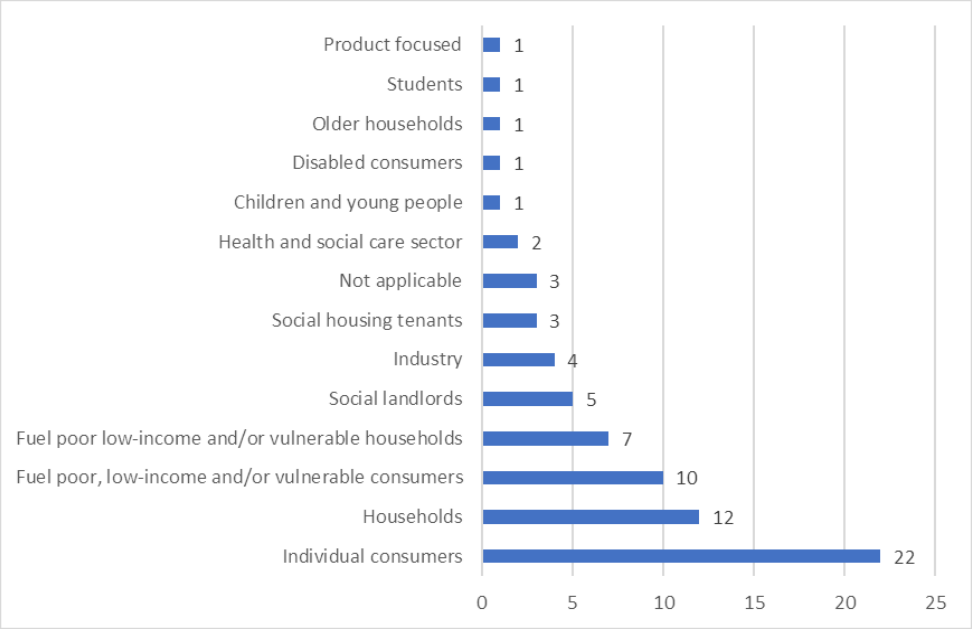
Figure 10: Source of publication of industry and policy literature



Finally, with regards to the unit of analysis, the industry and policy literature focused on a range of different units that are not reducible to the individual/household typology identified in the academic literature. Industry and policy literature tended to focus on individual *consumers* (n=22) or households (n=10) as opposed to individuals or households, and many works identified focused specifically on fuel poor, low-income and/or vulnerable consumers (n=10) or households (n=7). The distinction between the consumer and the household was in practice blurred in many of the studies examined, but is retained in the classification in Figure 11 to distin-

guish between studies that focused primarily (even if implicitly) on the barriers and enablers of Smart Home adoption for individual consumers, and the barriers and enablers for households (i.e. the house and its occupants together as a functioning technical, social, and economic unit). Moreover, several studies focused on a specific group of consumers or households that might be described as vulnerable, such as children and young people (n=1); social housing tenants (n=3); disabled consumers (n=1); students (n=1); and older households (n=1). Some studies focused on other actors involved in the development, innovation, and installation of Smart Home technologies, especially social landlords (n=5); industry (n=4); and the health and social care sector (n=2). One study was product focused (n=1). Finally, some studies did not have a defined or identifiable unit of analysis, and are defined in Figure 11 as not applicable (n=3).

Figure 11: Unit of analysis in the industry and policy literature. Note figures do not add up to the total number of studies examined because some studies had multiple foci of analysis.



Technologies related to Smart Homes

The discussion of technologies related to smart homes in the reviewed articles is broad. Therefore, a semantic categorisation approach was applied to identify the technology focus/type frequently associated with smart homes in the reviewed papers. Through this approach, the identified technologies were classified based on their focus/type.

- Security/privacy smart home system
- Information and communication technology (ICT)
- Home electrical appliances
- Energy sensor technology
- Home smart appliances e.g., smart light bulbs, smart plugs
- Internet of Things (IoT)
- Smart home devices: smart meters, smart thermostats, smartphone
- Renewable energy systems: photovoltaic/solar/electricity grid/battery storage
- Renewable heating technologies: heat pumps, hydrogen, district heating
- Smart heating controls, e.g., thermostats, TRVs, central timers
- Home healthcare smart system / smart assisted living technologies
- Artificial Intelligence (AI) e.g., machine learning
- General smart home technology
- Smart meters, including smart water meters
- Smart vehicle-to-grid integration of electric vehicles (EVs)
- Smart tariffs (e.g. Time of Use)

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Industry and policy references start with [I] to easily distinguish from the academic are only referenced by number.

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