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Smart home technologies in Europe: A critical review of concepts, benefits, risks and policies

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A R T I C L E I N F O

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A B S T R A C T

Smart home technologies refer to devices that provide some degree of digitally connected, automated, or enhanced services to building occupants. Smart homes have become central in recent technology and policy discussions about energy efficiency, climate change, and the sustainability of buildings. Nevertheless, do they truly promote sustainability goals? In addition, what sorts of benefits, risks, and policies do they entail? Based on an extensive original dataset involving expert interviews, site visits to retailers, and a comprehensive review of the literature, this study critically examines the promise and peril of smart home technologies. Drawing on original data collected in the United Kingdom, which has access to European markets, the study first examines definitions of smart homes before offering a new classification involving 13 categories of smart technology covering 267 specific options commercially available from 113 companies. It situates these different technology classes alongside six degrees or levels of smartness, from the basic or traditional home to the fully automated and sentient home. It then elaborates on the 13 distinct benefits smart homes may offer alongside potential 17 risks and barriers, before introducing seven policy recommendations from the material. It lastly suggests three areas of future research on the demographics and behavior of actual smart home adopters, rethinking the duality of "control," and looking beyond "homes" towards socio-technical systems, practices, and justice.

1. Introduction

Smart home technologies refer to devices that provide some degree of digitally connected or enhanced services to occupants [1], and are often synonymous with "home automation systems [2]." Smart homes have become central in recent technology and policy discussions about energy efficiency, climate change, and innovation (to name a few).

For example, multiple studies emphasize the criticality of smart home technologies for achieving "net energy buildings," "zero energy buildings [3]," and "life cycle zero energy buildings [4]." Others talk about the necessity of moving building stock towards "home automation" and "intelligent systems" to reduce resource use [5]. "Smart homes" are one of the ten pillars in the European Union's action areas for strategic investments in energy [6]. In the United Kingdom, the Office of Gas and Electricity Markets emphasizes that "smart homes and businesses" are key to their plans to achieve the further decarbonisation of electricity as well as integrate more substantive demand response programs [7]. Forecasts therefore suggest that the smart home technology market will grow substantially, and that they could become a defining factor of future energy transitions [8–10].

Indeed, Jungwoo et al. already estimate that smart home technologies had diffused to 7.5% of households globally and generated expected revenues of $44.2 billion in 2018 [11]. Market analysts Berg Insight estimate that at the end of 2017 there were 22.5 million smart homes in Europe alone, or 9.9% of European households [12]. They forecast a growth of ~30% a year, or 84 million smart homes by 2022, with France, Germany, and the United Kingdom leading the European market [13]. David et al. similarly predict that by 2020, 35% of all households

Abbreviations: SHT, Smart home technology; RD&D, Research design and development; BEIS, Department for Business, Energy & Industrial Strategy; ICT, Information and communication technology; IT, Information technology; IoT, Internet of Things; AI, Artificial Intelligence; NHS, National Health Service; LPWAN, Low-power Wide-Area Network; MLP, Multi-Level Perspective; ANT, Actor Network Theory; SCOT, The Social Construction of Technology; TIS, Technological Innovation Systems; LTS, Large Technical Systems.

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in North America and 20% of households in Europe could be classified as smart homes [14]. In the United Kingdom alone, the country's Industrial Strategy talks about smart systems with an explicit policy to boost digital infrastructure "with over £1 billion of public investment [15]". The Clean Growth plan refers to smart systems as an elemental part of low-carbon growth, and lists government investments in clean technology RD&D, including £265 million for smart systems and £184 million in homes (including heat and energy efficiency) [16]. In addition, smart homes understandably are discussed as core elements within efforts to promote smart grids and smart cities [17]. They are lastly impacting the way we even talk about homes and the future, with new linguistic terms emerging to classify new forms of smartness. The industry has created a new word, "pleasance," to underscore how smart homes can blend convenience and pleasure in ways to enhance feelings of comfort, peace of mind, and even romance [1]. Schill et al. add that smart home technologies are often adopted for such non-functional and non-utilitarian benefits such as symbolizing wealth, altruism, or a commitment to sustainability [18].

However, in this study, we critically examine the potential perils of smart home technologies alongside their promise, together with a broader range of sustainability dimensions, emphasizing not only energy and climate attributes but also issues related to privacy, trust, demographics, politics, and socio-technical systems. We utilized a mixed methods, rigorous research design to examine the types of smart home technologies currently available on the market in the United Kingdom, which has access to European suppliers, as well as to assess the benefits, risks, and complexities associated with smart home technology adoption. We collected primary data from 31 formal semi-structured research interviews with experts across six types of institutions, as well as structured site visits to 37 retail smart home technology providers across Bristol, Brighton, the greater London area, and Manchester in the United Kingdom. We supplemented this with an interdisciplinary review of the recent academic and policy literature on smart homes.

Our core contribution, apart from offering a remarkably up to date classification to the state of smart home technology development in Europe, is to also emphasize the social, cultural, behavioral, and even political dimensions of smart homes alongside technical and economic ones. In their recent systematic review of the smart homes academic literature, Marikyan et al. caution that "The literature predominantly focuses on the technical characteristics of smart homes, which means that there is a need for the adoption of the user perspective in research on the development of technologies [19]." Other reviews of the smart homes literature [20,21] or the smart mobility literature [22,23], find that most of it consists of technical studies focused on control and security, and such reviews call for a better understanding how adopters might use or otherwise interact with smart homes. We agree and designed our study to explicitly address this gap. Finally, our study offers concrete smart home policy recommendations for Europe, and elsewhere, and it also points to future research gaps and agendas.

2. Research design: expert interviews, retailer visits, and a critical literature review

Our two primary methods of data collection for the study were expert research interviews and site visits to retailers, complemented with a review of the academic literature.

The authors conducted semi-structured qualitative expert interviews. Our sampling strategy was purposive and designed to include experts from six different types of institutions:

- Government, including national ministries such as the Department for Business, Energy & Industrial Strategy (BEIS) and Ofgem as well as local government such as Bristol City Council;
- Academic institutions such as the University of East Anglia, Oxford University, Loughborough, and Nottingham;
- Private sector firms including energy suppliers such as Engie and NPower as well as software and technology companies such as Amazon and Microsoft;
- Civil society and independent research institutes such as Citizens Advice, the Green Alliance, Energy Systems Catapult, and Price Waterhouse Coopers;
- Industry and trade groups such as Smart Energy GB and the Alliance for Decentralized Energy;
- Intergovernmental organizations such as the European Commission and the International Energy Agency.

We conducted these interviews with 31 participants from November 2018 to February 2019. Although the bulk of our interviews were done in the UK, we still focused broadly on the commercial availability and viability of smart home technologies here in Europe. The research interviews generally lasted between thirty and 90 min, and participants were asked "What technologies, applications, services or options for smart home technologies (SHTs) are available here in the UK and Europe?" "What are their biggest benefits?" "What are their biggest barriers?" "What policy recommendations do you suggest?" All interviews were treated as anonymous to encourage candor and also protect respondents, although each was given a respondent number shown in Table 1. Most interviews were recorded so that transcriptions and statements could be checked for accuracy. After collection of the interview data, each interview was subsequently fully transcribed, and then coded. Our coding scheme was exhaustive and inductive, meaning we coded every response and then analyzed the full sample inductively.

In addition to interviews, we conducted structured site visits to retailers offering smart home technologies for sale on the market. We visited prominent retailers including:

- Direct suppliers of smart home technology such as the Apple Store, Samsung Store, O2 Store, and Vodaphone Shop;
- Do-It-Yourself (DIY) and home improvement stores such as IKEA, HomeBase and B&Q;
- General department stores or furniture shops with major smart home technologies on offer, such as Peter Jones, John Lewis, and the Conran Shop;
- Home electronics and household appliance retail stores such as Curry's PC World and the Carphone Warehouse.

We conducted visits to 37 of these retailers in January and February 2019 across eight Boroughs in the Greater London Area (Barnet, Brent, Camden, Croydon, Kensington and Chelsea, Hammersmith and Fulham, Newham, and Westminster) as well as Bristol, Brighton and Hove, and Manchester (see Fig. 1). These store visits, which lasted between 30 and 60 min each, had numerous advantages over merely looking at store catalogues or online websites. We were able to conduct additional short interviews and discussions with staff at the store, see what was commercially available and in stock (see Fig. 2), and also see how items were displayed, promoted, and in some cases discounted. Nonetheless,

Table 1
Summary of qualitative semi-structured research interviews for smart home technologies in Europe, 2018–2019 (n = 31).

Institution type	Respondents
Academia (n = 13)	R5, R6, R8, R9, R2, R12, R21, R22, R24, R26, R27, R28, R30
Civil society and consultancies (n = 5)	R14, R20, R23, R11, R13
Government (n = 4)	R1, R15, R18, R19
Industry groups (n = 2)	R25, R31
Intergovernmental organizations (n = 3)	R17, R3, R16
Private sector firms (n = 4)	R7, R4, R10, R29

Source: Authors

Fig. 1. Location of 37 structured site visits to retail home improvement, electronics, and household appliance shops in the UK, January and February 2019.
Source: Authors

although we visited a diverse number of retail firms, our sample was not exhaustive as it did not include others such as system integrators, consultants, building specialists or online sellers that are also a large part of the smart home market.

To triangulate our data from the interviews and site visits, and also to better situate it within the body of growing research, we lastly conducted an interdisciplinary literature review of smart home technologies studies published within the past twenty years (i.e., from 2000 to 2019). We searched the Scopus and Science Direct databases for terms such as "smart homes," "smart home technologies," "smart home services," "smart buildings," "smart living environments," "zero energy buildings," and "automated homes" as well as phrases such as "electricity," "gas," "heat," "mobility," "benefits," "barriers," "risks," "business models," "policy," "users," and "practices." The resulting corpus of approximately seventy studies is cited throughout this study to help situate our findings within the literature.

3. Historicizing, defining and conceptualizing smart home technologies

Smart home technologies have a much longer history than many may realize. The germination of an idea of homes that could be smarter in the comfort and convenience they provide can be traced back at least to the 1890s and early 1900s, when wealthy people used the introduction of electricity to create homes with greater degrees of automation and levels of luxury, relaxation, and indulgence [20]. As Fig. 3 reveals, Thomas Edison himself patented automated, colored lighting for homes as early as 1910, used later that year to promote public advertising for New York Edison. Similarly, the Rural Electrification Administration in the United States actively promoted during the 1930s an array of "modern" electric appliances to go hand in hand with efforts to electrify rural farms. General Electric and Westinghouse launched the "Live Better Electrically" campaign in 1956, efforts that awarded homes a gold medallion if they converted all of their appliances to electricity.

Since the 1990s and 2000s, smart homes have again arisen as cornerstones of making homes both more efficient (and lower in terms of energy consumption or carbon emissions) as well as more pleasurable and enjoyable. Table 2 offers a collection of 11 definitions of a "smart home" dating back to 1992, from Lutolf's notion that it involves common information and communications systems, to Marikyan et al.'s notion it involves state of the art technology that will offer tailored services to end users. Indeed, Appendix I supplements this discussion with 31 other definitions offered by our expert interview respondents. Alongside these definitions, a range of diffuse terms have arisen to describe smart homes, including "smart home services" and household "internet of things" [24] "intelligent electronic devices" and "home and building automation," [25] "private homes based on information and communication technologies (ICT)" [26] and even "non-stereotypical homes" for "human-computer interaction [27]."

Admittedly, much incoherence and definitional slippage exists within the literature. As R2 noted in our interviews, "*There is a lot of definitional confusion over what a smart home is or what counts as SHTs. Some people think smart phones, some narrowly on smart energy*." This point was also raised by R5*: "It is a bit of a grey area."* That said, modern SHTs seem to possess at least three core attributes. They enable a greater degree of control or functionality via monitoring and sensor interfaces [35]. They are networked or layered, connecting different technological features in a way to optimize service delivery and or performance [31]. In other terms, they layer together energy systems, digital systems, information systems, Internet of Things, data sharing, and even non-digital infrastructure [36]. They finally can empower, enabling or facilitating users changing their behavior, or doing things they could not

Fig. 2. Smart home technology on display at Westfield White City, London, 2019.
Source: Authors

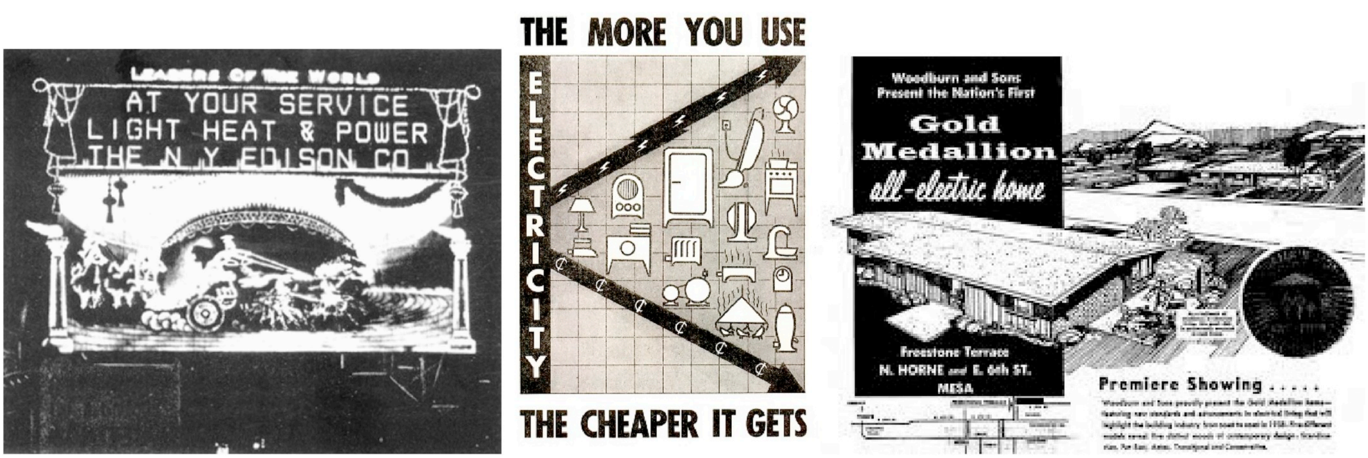

Fig. 3. Efforts at Smart Lighting and Homes from Thomas Edison (1910, left panel), the Rural Electricity Administration (1933, middle), and General Electric and Westinghouse (1956, right panel).
Source: Compiled by the authors

do before.

Smart home technologies can also lead to, or reflect, very different conceptions of what a home is for. It challenges or expands the very meaning of a home [37–40]. Gram-Hanssen and Darby for example distinguish four very different conceptions of a home—a controlled and secured space, a site of activity and practices, a place for relationships and continuity, an expression of identity and values—and how this maps onto four very different schools of conceptual, technical, prospective, and evaluative smart home research [20]. Hargreaves, Wilson and colleagues differentiate between functional, instrumental, and socio-technical views of a smart home, with each leading to different views of what a smart home is and does, shown in Table 3. As we will see later, our benefits and barriers cut across these different views and dimensions.

4. Plentiful commercial options and a spectrum of smartness

Our empirical material—collected via the expert interviews, retailer visits, and literature review—identified a staggering and surprising number of smart home technology options available on the market in

Table 2
Eleven prominent definitions of smart home technologies, 1992 to 2019.

Source	Date	Definition
Lutolf [28]	1992	The integration of different services within a home by employing a common communication system. It assures an economic, secure and comfortable operation of the home and includes a high degree of intelligent functionality and flexibility
Aldrich [29]	2003	A residence equipped with computing and information technology, which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home and connections to the world beyond
De Silva et al. [30]	2012	A home-like environment that possesses ambient intelligence and automatic control, which allows it to respond to the behavior of residents and provide them with various facilities
Balta-Ozkan et al. [31]	2014	A residence equipped with a communications network, linking sensors, domestic appliances, and devices, that can be remotely monitored, accessed or controlled and which provide services that respond to the needs of its inhabitants
Saul-Rinaldi et al. [32]	2014	Inclusive, two-way communication system between the house and its occupants
Buildings Performance Institute Europe [33]	2017	A smart building is highly energy efficient and covers its very low energy demand to a large extent by on-site or district-system-driven renewable energy sources. A smart building (i) stabilizes and drives a faster decarbonisation of the energy system through energy storage and demand-side flexibility; (ii) empowers its users and occupants with control over the energy flows; (iii) recognizes and reacts to users' and occupants' needs in terms of comfort, health, indoor air quality, safety as well as operational requirements.
Hargreaves and Wilson [34]	2017	A smart home collects and analyses data on the domestic environment, relays information to users (and service providers), and enhances the potential for managing different domestic systems (e.g., heating, lighting, entertainment)
Strengers and Nicholls [1]	2017	The smart home encompasses home ICTs, connected and automated devices and appliances, and the Internet of Things.
Shin et al. [11]	2018	An intelligent environment that is able to acquire and apply knowledge about its inhabitants and their surroundings in order to adapt and meet the goals of comfort and efficiency
Gram-Hanssen and Darby [20]	2018	One in which a communications network links sensors, appliances, controls and other devices to allow for remote monitoring and control by occupants and others, in order to provide frequent and regular services to occupants and to the electricity system
Marikyan et al. [19]	2019	A residence equipped with smart technologies aimed at providing tailored services for users

Table 3
Functional, instrumental, and socio-technical views of smart home technologies.

	Functional view	Instrumental view	Socio-technical view
What is the smart home?	A monitored, sensed environment that informs occupants allowing active control or automation	An optimally-managed building energy system allowing information and price-responsive adjustments to behavior	A digital, technological, networked vision confronted by the mundane realities of domestic life
	A set of inconspicuous technologies offering multiple remote and automated opportunities to control the domestic environment	A domestic energy management system for cost and convenience	(Yet another) set of technologies and devices to be integrated with existing domestic appliances and routines
What is the purpose of the smart home?	Improve quality of home life through new services and enhanced functionality	Enable energy demand reduction in the home and improved system management by utilities	No inherent purpose, functions emerge as SHTs are incorporated into domestic life as part of digitalisation of homes
	Enhancing lifestyle and domestic life by improving convenience, security, entertainment and communication	Controlling heating and energy-using appliances, and linking energy consumption to household lived experience	Making control and monitoring of homes and appliances easier and more convenient as part of a long-running dynamic towards modernising homes

Source: Modified from Refs. [21,34].

early 2019. As Fig. 4 reveals, we noted 267 different technologies commercially available across the 13 categories of household appliances, lighting, energy and utilities, entertainment, health and wellness, safety and security, baby and pet monitors, clothes and accessories, vehicles and drones, home robots, gardening, integrated solutions, and "others". These were provided by 113 different companies, literally from ADT to Zipato, although many Fortune 500 companies were involved in well, including Apple, Amazon, Microsoft and Google as well as Nissan, Nike, Sony, Garmin, Samsung, Siemens and Philips. The full list of all 267 options is offered in Appendix II. Although this number may seem vast, it is similar in size to the 313 home energy management products identified and analyzed by Ford et al. [41].

As Appendix III reveals, this fecundity of options was not an isolated occurrence. During our shop visits, 23 shops had at least four different categories of smart home technologies available, and six shops had 10 classes or more of smart home technologies available. In terms of the categories of smart home technologies most available, 29 shops (of the 37) had smart safety and security devices, 27 shops integrated solutions, 27 shops smart clothing and accessories and 25 shops smart lighting. Even the two classes of least frequently available smart home technology options, baby and pet monitors as well as gardening, were still present in 5 of the shops.

Not all of these smart home technology options have the same level of smartness. Instead, our material suggested there were degrees of smartness. Marikyan et al. [19] for example identify a spectrum of smart home types, from moving between a "traditional home" up to a "fully smart one." As we suggest in Fig. 5, a "dumb," "basic," or "analogue home," at level zero, has no smart home technologies. A level 1 home has a few smart home devices, such as a television or baby monitor or a solar photovoltaic (PV) system, and perhaps basic levels of feedback, but occupants still decide in an analogue way how to engage, and the technologies are not interconnected and remain in silos.

A level 2 home starts to see technologies bundled together and integrated to better provide some household services, such as heat (perhaps a smart meter with in-home display plus heat pump and advanced thermometer) or entertainment (perhaps a smart TV coupled

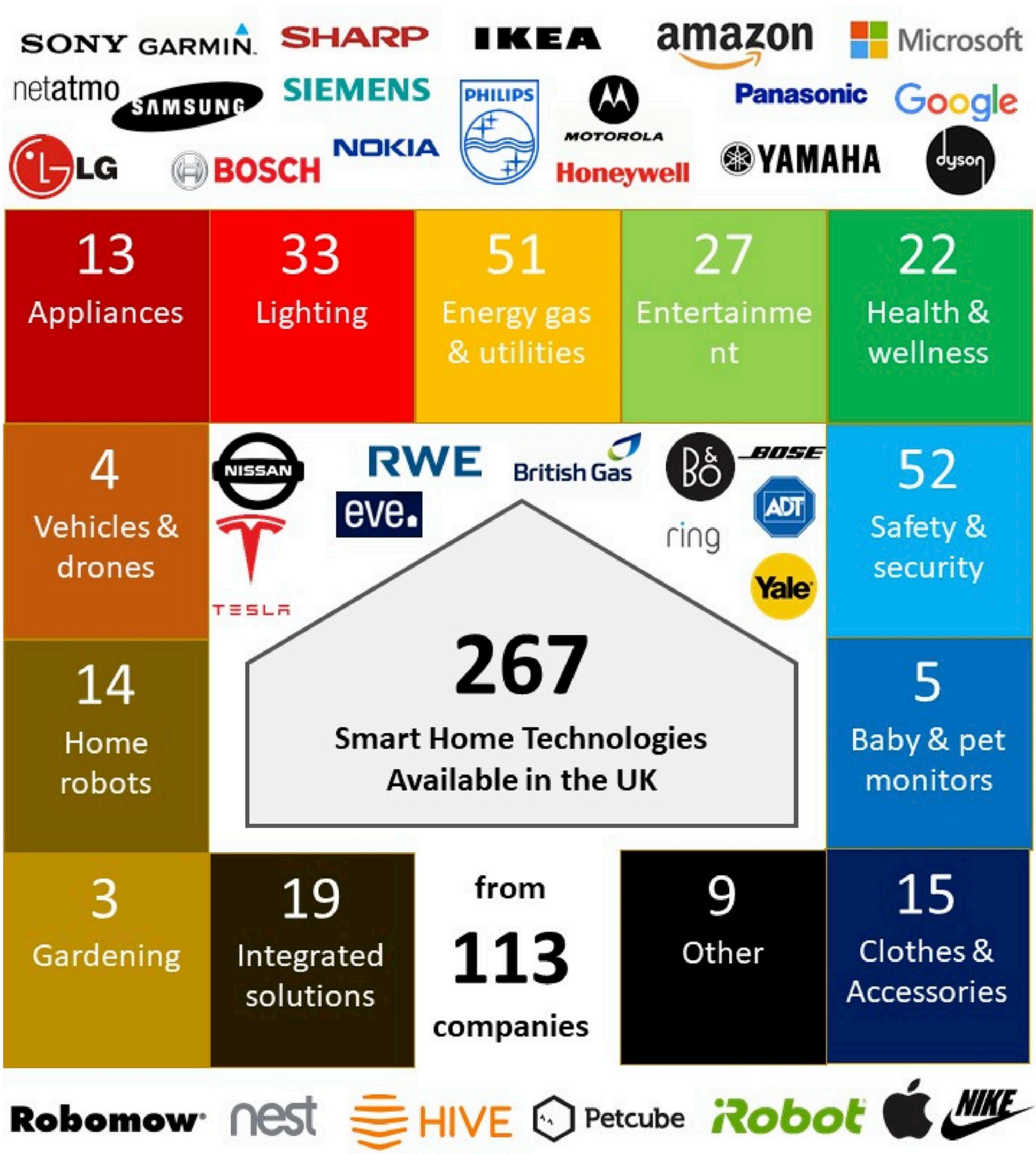

Fig. 4. Smart home technology options available in Europe, 2019.
Source: Authors

with an internet router, audio sound system, laptop, and mobile phone).

A level 3 home moves towards some degree of greater automation, with systems beginning to interconnect and even anticipate certain needs, such as turning lights or appliances on a few moments before an occupant returns home. A level 3 home can also be programmed to meet certain preferences across multiple devices, including different temperatures in different rooms.

A level 4 home sees systems begin to actually learn for themselves and adapt their provision of services to context, i.e. turning the lights on if a storm is coming, or turning them back off when the sun comes out. It is at this level where sensors and monitors can enable technology to know the conditions of the home, and feedback loops can facilitate some learning so it becomes more autonomous and can adapt to what it thinks you want.

A level 5 home becomes almost sentient, and can automatically meet and even anticipate all household needs. At this highest level, monitoring, feedback and learning coalesce across multiple integrated systems (heating, lighting, gardening, mobility) so that the house itself can seamlessly provide services. Homes at this level would most likely start talking to occupants, and also perhaps each other. This would be an "artificially intelligent" home or one that is "fully smart." One salesperson we visited at John Lewis joked that at this level, *"We will not do anything in a couple of years, these appliances will do everything for us!"* A level 5 home thus moves beyond mere smart control or smart automation to smart home sentience. Within the literature, designers are even discussing how smart homes can become integrated into virtual reality so that the empirical and physical world merges with what they have termed "substitutional reality [42]." This would blend smart home sentience with an ability to create entire virtual worlds and realities.

Some respondents discussed a possible sixth level, beyond that of a single home, of smart neighbourhoods, communities, and cities. These would be comprised of interconnected level 5 smart homes with

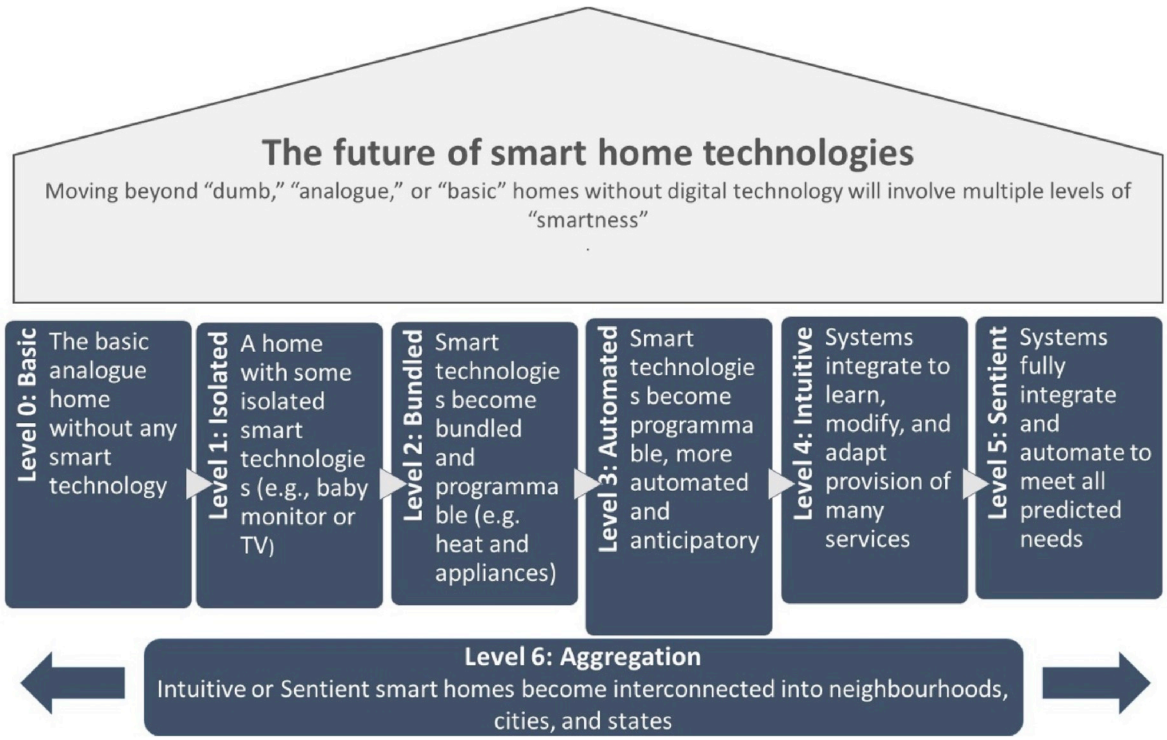

Fig. 5. Levels of smartness with smart home technologies.
Source: Authors

complex baskets of interconnected smart home technologies. As R12 noted, "*this level goes beyond the house or mere smart kit to the true smart grid or smart society.*" We will return to this level in our section on a future research agenda.

5. Contextualizing the potential benefits of smart home technologies

Our material culminated in at least 13 different types of benefits smart home technologies can offer households, businesses, or society. Table 4 offers a frequency analysis of these 13 benefits across our interviews, with the most popular being energy savings, convenience and controllability, and financial benefits. Admittedly, this list of benefits blends together realistic, observable and more near-term benefits with those that are more distant, hopeful, and long-term. Nonetheless, in doing so, it certainly expands upon the exiting literature on benefits. Balta-Ozkan for example classified only seven types of benefits across the three classes of energy consumption, safety, and lifestyle support [31]; the systematic review from Marikyan et al. identified only five classes of benefits (comfort, monitoring, health, and support, consultancy) [19]; Hargreaves et al. identified four distinct motivations to adopt smart homes in their work: saving energy, interest in new technology, protecting the environment, and a desire for improved control [43]; Gram-Hanssen and Darby argue that the two areas of greatest interest are "health care" and "energy consumption of management [20]".

Table 4
Thirteen smart home technology benefits discussed by expert interview respondents (n = 31).

Rank	Frequency (by interview)		Topic
1	25	80.65%	Energy savings
1	25	80.65%	Convenience and controllability
2	15	48.39%	Financial benefits and saving money
2	15	48.39%	System benefits for grids, networks, operators
3	14	45.16%	Environmental benefits including carbon, pollution, waste
4	13	41.94%	Aesthetics including style, design, feel, and fashion
5	11	35.48%	Health benefits and assisted living
5	11	35.48%	Social benefits including inclusion, networking, status
6	9	29.03%	Educational benefits and learning
6	9	29.03%	Entertainment including music, movies, streaming
6	9	29.03%	Safety and security
7	8	25.81%	Other enhanced experiences (e.g., shopping)
8	4	12.90%	Free services or promotional gifts

Source: Authors

The most prominent benefit mentioned was the ability for smart home technologies to better manage energy services or reduce energy consumption. This relates partly to how *inefficient* the building stock is in Europe, especially the United Kingdom. For instance, one survey of 21,900 homes in England noted that 98% had a gas boiler for central heating (so no heat pumps or district heating) and that these had only simple controls such as an on/off switch or a timer [44]. It also noted that heating density plots show that people just leave heating on all the time from morning to night. Similar evidence from the government suggested that of the 95% of all United Kingdom homes that have a boiler, 800,000 have no controls at all, and almost 8 million have no room thermostat [45]. This could explain why space heating and hot water is responsible for 75% of domestic energy consumption [45].

Thus, as R2 noted, "*the biggest or best potential for smart home technologies relates to reducing energy demand and better demand management.*" As one example, trials of smart heating controls alone suggest they could *save* something like a 5–7% annual reduction in household energy consumption [46]. R15 added, "*Controlling energy and awareness of how much energy houses are using is a key benefit, as it creates opportunities to save, reduce, or optimize when you use energy*." R31 mentioned how in market surveys they have undertaken, "*half of people they interviewed who had a pet heated their house all day, to keep pets warm, when veterinary associations indicate this is not needed. This is a massive waste of energy that smart devices can address.*"

An equally prominent benefit was improved convenience and controllability over a household. As R2 put it, "*many smart home technologies aren't about saving energy, they are about convenience and controllability, hence this interest in voice control such as Alexa, and such technologies make life easier, more fun, and more interesting.*" R12 added, "*The most important benefit for most people is the comfort, convenience and control that smart home technologies can offer*." R23 mentioned "*Anything that make consumers life simpler is a benefit, anything that helps them reduce their mental load on tasks*" whilst R13 mentioned on a similar way that: "*Anything that makes you more comfortable and easier for you to get the outcome you want without having to consciously think about how to achieve that outcome.*"

Financial benefits such as saving money came third, and include the ability for households to better monitor spending and also switch to better tariffs and cheaper service providers. As R13 stated, "*from an energy standpoint, even in general terms, positive outcomes can be becoming more consciously connected and aware in ways that save you money*." With this in mind, R11 suggested that "*smart homes should increase the engagement of the consumer with different markets. That has huge potential savings for the customers*".

The fourth most mentioned benefit for SHTs was system benefits for grid operators, with R15 commenting that "*the industry benefits from smart home technologies through better data and no longer needing to do manual meter readings*." In terms of automation and efficiency, R22 said "*This could also have benefits for the systems operators, it could be the distributors or the national system operators, and they have the benefit to balance supply and demand with greater control … this could allow them to come up with complete new business models and service offering*". R28 stated that "*There are benefits for the electricity grid too, you can better manage demand and then you have better data which allows you to better control power stations*". R27 pinpointed how smart home technologies could enhance services: "*indeed, smart homes are becoming more useful because the datasets are getting bigger, the algorithms are getting better and therefore, some companies are learning lots on behavior. Which allows them to optimize and to provide better services*".

Environmental benefits included displaced carbon, pollution, or waste, achieved through a mix of better monitoring, better energy management systems, and greater control over the sources of domestic carbon emissions. Energy savings are predicted as remotely accessible apps and displays raise household awareness of their energy consumption and allow them response from a distance, and allow for real-time notifications. In addition, data analytics could allow urban planners, utility companies and architects to understand demand patterns for better planning and maintenance. The Accenture report, which was produced for Global e-Sustainability Initiative (GeSI) – a global ICT industry association - estimates that ICT avoided emissions are equivalent to 9.7 times the ICT sector's "emissions footprint [47]".

In this context, R18 noted: "*if households became flexible users of energy that could increase the amount of intermittent renewable energy that could penetrate in the grid. By having homes that are using energy at the time when the grid needs it, would result in an environmental win, even if we weren't using less energy*". R31 suggested that "*individuals might feel that helping the environment is quite a big task, so if you can introduce smart home technologies which allow things like automation, it takes that difficult decision out of your hands and it actually knows when the grid is generating the greenest energy*". R29 highlighted the importance of these technologies in tackling climate change: "*consumer engagement … is going to be absolutely essential to hit our 2050 goals and then the goals that will continue after … the trilemma cannot be achieved without these technologies and will be achieved with their use.*" Hence promotional material such as Fig. 6, noting that adopting smart meters in the UK will *save* as much carbon dioxide as planning 10 million trees.

Aesthetic benefits include liking how smart home technologies look, are designed, and add symbolic value to a house as an item of fashion or style. R4 stated that "*People are positioned more in the emotional and aspirational side of the home, rather than the benefits. People want to have these technologies in their homes because it looks really cool and it's*

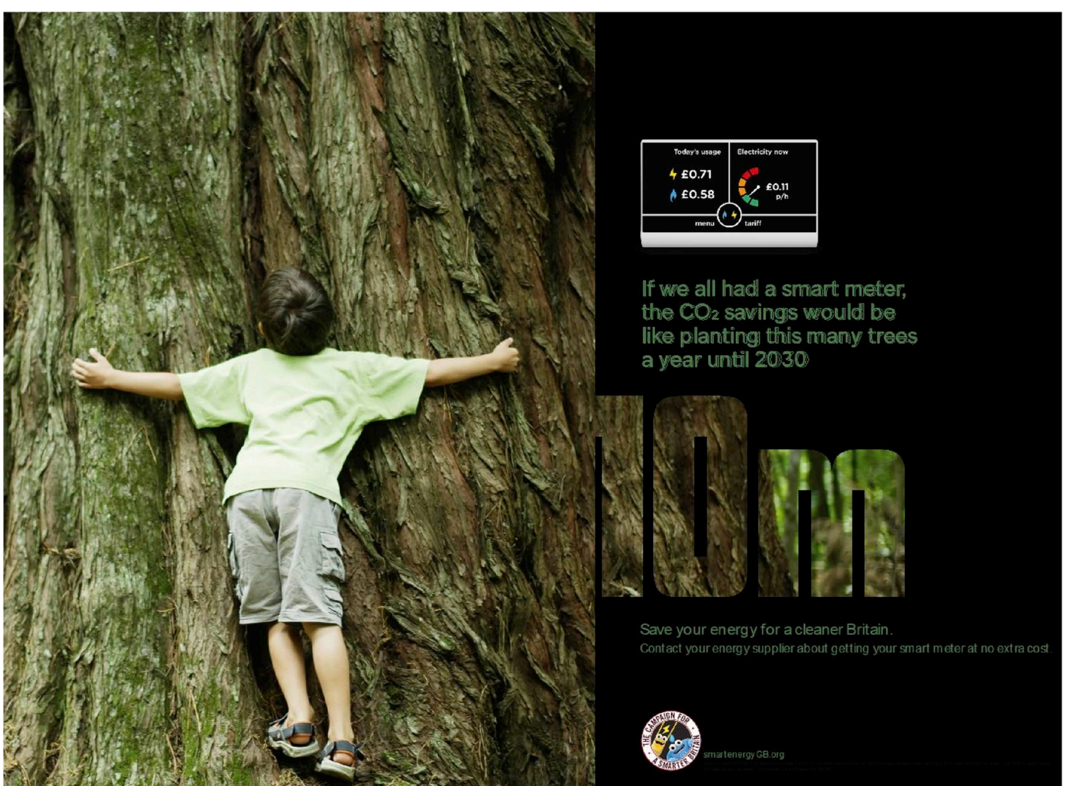

Fig. 6. Smart meter advertisement from Smart Energy GB, November 2018.
Source: Smart Energy GB

something you can show off to people and it is like: hey, I'm futuristic." R12 stated, "*Smart home technologies are currently driven by status – not environmental motivations. It's technophila, rather than technophobia, with people needing to possess and purchase the coolest gadget to have*." As R14 added "*To some people, the benefits of adoption relate most to aesthetics, to people just being drawn to beautifully designed or new things, to show they are ahead of the curve*."

Health benefits include the ability to alert relatives or health professionals to emergency events, aiding health diagnosis, and enabling aggregate level health analytics [48]. Such health benefits can be particularly acute for the elderly and aging, vulnerable people, or people with chronic medical conditions [19]. Confirming this benefit, a systematic review of smart homes and older adults with chronic illnesses did find that smart homes had a positive effect on physical functioning and depression [49]. As R14 stated, "*assisted living is very interesting, enabling people to live at home longer or to live healthier lives. Charging an eclectic wheelchair, or figuring out treatment regimens for extreme medical conditions, or having NHS prescription medicines monitored, reordered and delivered automatically*." R11 linked smart homes and mental health: "*Some of the signs of people with dementia is that they forget to drink water and therefore they become dehydrated. So there are companies looking at putting controls in the house to measure how many times the kettle is boiled, how many times the toilet is flushed, so they can use this data to actually track if people are actually drinking water.*" And finally, R23 noticed the deployment of smart health technologies carried out by energy suppliers: "*I know British Gas are increasingly looking at health stuff, like they can see if your grandma has put the kettle in the morning, so you are now able to monitor the vulnerable ones*".

Social benefits related to inclusion—adopters feeling like they belonged to a community—or networking with others for professional or personal reasons. This relates to smart homes enabling people to better socialize and overcome feelings of depression or isolation. As R6 explained, "*SHTs can become a way of being positively connected to others.*" R14 surmised that *"other benefits can be about connecting you to people who you love*". R23, mentioned that the main benefit of smart home technologies would be inclusion: "*I think the main benefit is helping people navigate in an increasingly confusing world.*"

Educational benefits related to the enhanced learning opportunities smart home technologies can bring, whether accessing new forms of knowledge, undertaking digital training, or simply new ways of receiving information or developing new skills. During one of our site visits to the Apple Store, a salesperson remarked that "*Some of the robots we have here are not only for children. Adults can use them too and learn how to code. In a way, I think all this new stuff is quite interactive and is pushing a new way of learning.*" R28 perceives smart homes "*as a platform of information in which you can coach and provide better services to the population*". R27 also mentioned that smart homes "*could be a way to learn more about the performance of your home and then, optimize your own heating cycle based on what do you know. So either you can cede control or you can take it back.*"

Entertainment benefits centered on easier or better ways of listening to music, watching movies, or online streaming. R25 identified entertainment as a key benefit, since people demanded it this feature: *"people want to watch Netflix, so you need an internet enabled TV, so no TV manufacturer is going to make one that it isn't. That is where the smart technology is simply delivering something that consumers really want. And yes, it is a self-reinforcement circle in the sense that somebody didn't know they wanted Netflix, but when they bought the TV, they had the possibility and explored it … there was a consumer desire for this service and the smartness just delivered that.*" R28 identified entertainments as a hook to educate: "*It is difficult to disentangle education and entertainment; you want to be educated and you want to be taught but it has to be entertaining otherwise you might not sign-up for those programs. I think the hook starts with entertainment and then you work from there*".

Safety and security related to notifying the police of emergencies or preventing fires and severe accidents. As R6 explained, "*Smart technology can prevent serious things happening, for example carbon monoxide detectors, smoke detectors, a way of turning off the heating if nobody is in the house. Detecting leaks, natural gas or water, serving a critical backup function*."

Other enhanced experiences came second to last (e.g., new forms of shopping), with R15 explaining that "*the hope is there will be additional apps built around smart home technologies that will create a smart ecosystem where new ways of shopping arise*." Whist R5 linked enhanced experiences with comfort: "*That is probably why Alexa is successful, it is very cheap and it does not do anything you were unable to do before. You could buy things on Amazon before by opening your laptop, now you just ask for it*".

A final category of benefits was the likelihood of smart home technology providers giving away free or promotional items to "members" of their own communities, from R16's "*free coffee*" to R30's *"a free iPhone upgrade every two years.*" R18 suggested: "*Another approach could be giving appliances for free, but then taking a cut as a company. So if you have an appliance that you believe would save the household money or generate it; if you really believe it as a company, then you could operate a model where the risk is with the company rather than the household to create that return of investment*". R28 added: *"I think most of these technologies are offering a payback period, so if you spend certain amount of money buying a device, after some time of using it, you will save enough to offset the cost. So if you are a company, you could offer these technologies for free"*. Indeed, in London in 2019, the authors already saw repeated advertisements for smart data services where one could get back additional data or convert it into cash for fundraising for hobbies or the "church roof."

6. Identifying potential barriers and risks to smart homes

These benefits do not come without risks and barriers, however, and our material led to the identification of no less than 17 of these shown in Table 5. By risks, we meant potential downsides to adoption, and by barriers, we meant factors impeding adoption. Given risks and barriers relate to each other, and were often discussed together in the interviews, we have grouped them together for our analysis. These cut across the more standard dimensions discussed in the literature, such as Hargraves and Wilson's classification of challenges across hardware and software, acceptability and usability, and domesticating technologies into lifestyles [34], or the Osservatori Digital Innovation del Politecnico di Milano, who suggests that the three main barriers to the smart home technology market are the installation of products, the integration of the

Table 5
Seventeen smart home technology risks and barriers discussed by expert interview respondents (n = 31).

Rank	Frequency by interview		Topic
1	25	80.65%	Privacy, security and hacking
1	25	80.65%	Technical reliability, warranties, and obsolescence
2	24	77.42%	Usability, user acceptance and learning
3	23	74.19%	Elitism, incumbency, barriers to market, and erosion of democracy
4	20	64.52%	Uncertainty, lack of sharing, and difficulty monetizing benefits
5	15	48.39%	Interoperability and resilience
6	14	45.16%	Energy rebounds and wasteful consumption
7	9	29.03%	Loss of personal control and autonomy
8	8	25.81%	Resource intensity, materiality, and sustainability
9	7	22.58%	Lack of home ownership
10	6	19.35%	Cultural differences to global diffusion
10	6	19.35%	Poor connectivity, lack of standardization, and supply chains
10	6	19.35%	Corporate longevity, accountability, and consumer choice
11	5	16.13%	High cost
11	5	16.13%	Fear of new technology
12	2	6.45%	Social isolation and loneliness
13	1	3.23%	Health

Source: Authors

offer with valuable services and the presence of established brands [50].

As perhaps expected by the literature, the top two barriers and risks related to concerns about consumer protection and data security, as well as technical reliability and smart home technologies working properly and not becoming quickly obsolete. In order to maximize their efficiency and performance, and also to move up to greater levels of smartness (See Fig. 4), smart homes need to collect a great deal of information about houses, affiliated technologies (such as appliances and even vehicles), user demographics and consumption patterns. However, this creates a severe risk that such data can be stolen, hacked, or misused. As R12 stated, "*At the highest levels of smartness, homes are especially most vulnerable to hacking and security breaches. So it's a paradox, the smarter your home is, the more vulnerable you become. Current security experts talk about how even a simple smart device like a toaster can be an entry for a hacker into the entire home. It creates a soft digital underbelly that thieves and hackers can exploit.*"

A related concern is whether the companies collecting this data, notably Google or Facebook, can be trusted. R27 suggested that the only real risk with the deployment of smart homes technologies is data: "*Ultimately this is really about being able to identify you and your home and the status of your home at any given time. That is the real risk it starts to reveal very personal data. So companies out there, can you trust them with your data?*"

The other top barrier and risk related to technical reliability and obsolescence. The smarter homes become, the more complex and interconnected they are, but that could also create dependences that can erode reliability—for instance, many smart devices would simply not work in an electricity blackout, or may confuse a cat with a burglar. R2 noted part of this concern can be due to faulty installations and lack of familiarity with new devices. As they elaborated, "*In our own trials of smart home technology, gas engineers and electricity engineers not familiar with the technology botched some installations or put things in backwards.*" R6 added that "*smart systems are layered and interdependent. A smart home is really using two sociotechnical systems, the electricity system layered on top of the IT system. One cannot work without the other, the lack of one can cause failure of both. We need to expect in smart systems that we will have problems from time to time, because they are clever, complex, and require expert knowledge, we need to keep our expectations realistic, and always have a plan B*." R12 noted that even when they are properly installed, there is "*the risk of performance and systems crashing. We already expect smart phones or laptops to start to perform worse after a year or two, their screens freeze, they get viruses, they need to frequently restart. Imagine now that these problems afflict your home. Even if you only have to restart a whole home on an infrequent basis, it can still be a major hassle.*"

Other respondents discussed built in obsolescence and the speed of innovation within the sector. R6 stated that a major issue is "*permanence, or rather impermanence. There will always be a subset of the population who buys the SHT bells and whistles stuff. They will use it for a bit, may use it if they are on their own, quite a lot, but over time they may get tired of it, and use it less, especially if it breaks, or needs upgraded. And upgrades can be related to hardware (becoming obsolete or out of date) but also software*."

Usability and learning came up next, and include that many smart home devices may be perceived as not being easy or intuitive to use, not only by households but other elements of the smart ecosystem. They require uses to "adapt" or "domesticate" them into their lifestyles. R6 framed this challenge in terms of "*Smart home technologies require user learning, but learning isn't limited to users. System operators and business facilitators also have to learn, so do regulators, learning occurs across all of these [actors], and accountability becomes even more important in a smart system, precisely because it is so distributed*." Pilots of smart heating controls for example have found that previous familiarity with smart homes helped make adoption easier, same with previous experience using touch-screens [51]. Hargreaves and Wilson suggest that smart home technologies must also not overwhelm or overpower possible users with too many options or difficult to utilize controls [34]. R3 brought this point too*: "Not everybody would like … too many choices of smart design."*

R3 also distinguished between different types of learning necessary for adoption: practical learning (how to configure and use the technology), cognitive learning (understanding what they can do or be used for), and symbolic learning (incorporating devices into routines and practices), something that also arose in Ref. [34]. When any of these forms of learning break down, users can become frustrated—with some smart home users staying that "*it wasn't intuitive what parts of it you can do straight away*" and "*It's too bloody complicated and there's no point in it and it's doing me no benefit, not worth it* [43]." R22 illustrated usability with the following example: "*I read the other day that someone bought a smart kettle and he spent 11 h trying to boil the water with the smart kettle, because there was so much setting up to do and connecting things. This technological wonderfulness needs to work well to make life easier. I mean, logging-in into your kettle is not probably as smart as switching on/off the kettle [yourself].*"

Perhaps surprisingly, issues centered on elitism, incumbency and market barriers, and the erosion of democracy came as the fourth most mentioned barrier. This relates to a perceived entrenching of market and political power among big smart home technology firms, who may use the data, revenues, or knowledge they collect to suit their own ends, rather than social goals of sustainability or poverty reduction [52]. R15 stated that "*With all technologies, there is always a risk of them being easier to use and access by some and not others. We would be interested in whether smart thermostats are useable, especially by people less tech savvy. Or those who are physically disabled. This is why we did usability tests and smart heating controls. Smart meters have also been looked at for vulnerable groups, and how to ensure that they benefit. The last thing we want is a smart system to only benefit some in society. We must always hedge against this distribution risk.*" R12 added that "*there is a risk in terms of companies and incumbency. Smart home systems are becoming the domain of big established companies, some of the biggest in the world, including Apple and Amazon but also Panasonic, Samsung, and Philips. This means the smart home* agenda *is controlled and dominated by a small number of voices with very big interests*." This consolidation of market power and data could, in the extreme, undermine democracy, entrench new forms of power, and threaten recent gains in equality. Given smart technology firms often operate in a regulatory environment that is opaque, loosely regulated when it comes to taxes, and prone to immense lobbying, a smart home society would create a "toxic cocktail for democracy [53]" or a new era of "surveillance capitalism [54]."

Uncertainty over the future as well as whether smart home benefits will be shared or monetized was mentioned as another frequent challenge. R22 illustrated monetization as a barrier in the following way: "*Another barrier, of course, from the commercial point is the monetization. So yes, you can provide smart fridge services but how do you actually get the money saved from the energy system … how do you prove that somebody avoided peak demand? Or how much energy they reduced compared to the counterfactuals of what the demand would have been? How do you get rewarded for grid services that at the moment are not reflected in household tariffs or contracts?*" R24 mentioned that "*There is a lot of niche stuff, smart light bulbs [for example] where you can change the color over again but you might get bored of it and never do it again. At the moment, the business case for smart homes is unclear, it seems more about novelty than anything else.*"

Interoperability and resilience captured the risk that not all equipment, devices, appliances, or systems will operate together, especially when they may be from different retail suppliers or use different networks and protocols. R6 cautioned that "*Interoperability issues and incumbency can get in the way of smart tech take-up. It may also mean people get left with stranded assets, some specialized piece of tech that no longer works, and the company making it has gone out of business*." Hargreaves and Wilson framed the interoperability challenge in three dimensions: needing smart home technologies that are compatible with non-smart homes and appliances, with busy lives and routines, and with existing support systems [34]. Interoperability is especially challenging given that it requires not only technologies to work together, but different smart home firms and operators to establish better cooperative relationships with providers, and that items can be replaced without disrupting the operational performance of a smart home [11].

Energy rebounds and wasteful consumption referred to the fact that many smart home technologies are not about saving energy or becoming more sustainable, but prioritizing other issues such as comfort, luxury, or convenience. R2 aptly noted that "*some emerging evidence, and intuition, says that smart tech can result in waste, hence the proliferation of robot lawn mowers or vacuum cleaners that are always on. Smart home technologies can embed more energy-intensive routines and practices, and do so more deeply and invisibly into our lives … Humans are remarkably creative at coming up with new ways to use energy … The human capacity to invent new ways to waste energy is profound.*" R12 agreed and noted that "*there is little evidence smart technologies have a positive effect on sustainability. They are driven by other, non-environmental desires that often lead to increases in energy demand … People who adopt smart tech feel good, embodied in the sensory feedback of the devices, and other people say they look good with their smart tech, so the whole thing works against a culture of energy demand reduction. The culture of the home focuses on high tech, but not thoughtful consumption, not on efficiency, or simplicity. It is not a culture that privileges energy demand reduction as key form of social feedback.*" There is thus a fear that increasing data and the "Internet of Things" could require a "tsunami of data" and greatly increase global electricity usage [55]. Strengers and Nicholls show how the convenience narrative full of smart devices could transform everyday practices in ways that increase not only energy consumption, but household labor [1], or lead to greater energy intensive loads for things like air conditioning or electricity [56]. Tirado Herrero et al. also find that smart home technologies can reinforce unsustainable energy consumption [57]. R30 commented on this aspect too: "*Overall I like the idea of smart homes, but like with every technological development there is this risk of rebound effects were you end up using more.*" For reasons such as these, Makhadmeh et al. caution that optimizing power demand for smart home appliances represents a significant challenge that future power suppliers will have to address [58].

Smart home technologies could lead to loss of personal control and autonomy, with households becoming more dependent on smart technology. This could create conditions where people serve the system, rather than having the system serve them. R2 called this the "*paradox*" of smart homes, that homes "*get [enhanced] control only by linking homes and heating to broader systems of provision, particularly the internet and digital technologies, connecting them into a broader network. Smart technologies with cloud based data, storage and processing provide more control and functionality, but also embed those individuals in a larger whole, a larger system. This makes it a relational dimension with mutual dependences*." R6 framed this in terms of "*an exchange of roles*," with the traditional model being about energy services for a household, but a new model can be "*the home is there only to provide services to the network … Smart is sold as being liberating, but that liberation comes with hidden dependencies. Smart stuff is so clever that only experts fully understand it, especially particular components such as the algorithms, which only the backroom boys know. We invest an extraordinary amount of trust and power in those who write the algorithms and who design the smart system. If something is going wrong with smart tech, chances are you won't be able to fix it yourself*." R12 lastly noted that in their perspective, "*the key risk is ceding autonomy and independence in the home. While smart systems are supposed to provide more control, because we don't fully understand how they work, we quickly end up out of control when things go wrong. When a smart tech fails, we need to ring somebody up to help fix it, these technologies are impossible to fix yourself.*" Indeed, a representative national survey of UK homeowners (n = 1025) found that ceding autonomy and independence in the home for increased technological control were the *main* perceived risks [8].

Although framed as efficient, many smart home technologies are resource or material intensive as well. Walzberg et al. note explicitly that more refined life cycle analyses are needed to compute the environmental impacts of smart homes across multiple indicators and stages of their product lifetimes [59]. R6 captured this nicely, when they noted that "*There is a risk of using smartness in an over-abstract way, something 'whizzy and weightless'. We used to have an IT support person who always said to us sternly, you think of the cloud as some abstract immaterial entity, but I think of someone else's physical computer or server. A cloud is lumps of metal somewhere, lots of processors, materials, and energy usage. In the same way, smart technology requires extraction and processing of an abundance of materials. It has meaningful and measurable social and ecological impacts, given that many of those materials come from troubled parts of the world.*" R20 stated that "the *E-waste risk is obviously bad, it is quite a hidden thing, and not many people have looked into the environmental footprint of the manufacturing of these devices. At the moment, I think just smart phones' annual production has the same carbon footprint as the whole of the UK transport sector and it is growing. That is just carbon in production, it has nothing to do with the end-of-life situation.*"

R12 added that a smart home revolution could even change our culture in ways that embed material consumption and notions of abundance: "*Smart homes become a way of showing off to friends but also demonstrating competency. So people who work at home—cooks, musicians, childminders—may start to indoctrinate the idea that to do these things well you need smart home systems. This can spread and change the dynamic and trajectory of energy practices in a more energy intensive direction across multiple households, adding to the treadmill of consumption, not slowing it down. It is social feedback the wrong way … Its sole purpose is to keep going further and faster along current trajectories, not about transforming the system or questioning its underlying assumptions*."

Lack of home ownership was another identified barrier, given that many times people need to own their own property, rather than rent or lease. Then, they often need to own an entire house, not just a room or a flat. R17 pointed out to this barrier in terms of incentives: "*Only around 20 to 30 percent of people actually own their apartments, the rest … rent.*" In a similar vein, R31 mentioned home-ownership as a key deterrent: "*There is a lot of people who aren't going to be incentivized to buy [smart tech]. Property ownership has been a huge barrier for smart meters.*"

Cultural differences could exist as another barrier, especially concerning global diffusion. R22 framed it as: "*It is quite interesting [to see] the cultural differences between Germany and the UK. Here [in the UK] we are quite casual with the personal data … in Germany, you have the living memory of the Stasi.*" R5 elaborated on global aspects of culture connected to political structures and deployment patterns: "*Europe is well ahead in this area because it seems to be a very pro-consumer approach. There are political structures that allow consumers' organizations to defend consumers. Whilst in the US, it is more driven by the manufacturers instead of government. That is how the system works, it is more like companies realizing what the downsides are. In parts of Asia it is more like Europe, other parts of Asia are more like the US. And there is China, where my favorite quote I heard from one of our potential customers was: 'I'm Chinese why do I worry about security? My government does that for me'*".

Other respondents discussed how lack of connectivity to the internet, such as in rural areas or the developing world, could greatly impede adoption. Also included in this category were barriers related to lack of proper standards and certification across smart home technologies and only nascently developed supply chains. R16 mentioned: "*in less developed countries, we're still talking very much about plain vanilla technology, both in terms of buildings construction, as well as the type of devices that they are putting in the market*". R7 added: "*Connectivity is a huge barrier, so even if Wi-Fi penetration is quite high, it is often incomplete in social housing. Also, if we look at Low Power Wide Area Network Systems or any other IoT there is a big question of infrastructure … one of the biggest challenges for the hardware providers is that nobody really knows who is going to win this IoT battle.*"

Corporate accountability, while similar to the erosion of democracy, was mentioned as a barrier more about companies honoring smart home commitments and being open and honest about problems and transparent about their marketing and promotional material. R27 illustrated this point by stating: "*If something goes wrong, can you get great customer service to get it fixed very quickly and could you seek redress for harm or any detriment caused? In an ideal world, it should not matter who you go to, with*

Table 6
Eleven smart home technology policy recommendations discussed by expert interview respondents (n = 31).

Rank	Frequency by interview		Topic	Dimension of sustainability
1	18	58.06%	Consumer protection, privacy, data security	Social
2	16	51.61%	Restrictions or configurations to ensure low-energy or low-carbon	Environmental
3	12	38.71%	Stronger regulations for energy services or Internet of Things	Political
4	11	35.48%	Provide research, innovation, and learning	Technical
5	8	25.81%	Remove barriers and encouraging market competition	Economic
5	8	25.81%	Provide knowledge, information and evidence	Social
6	7	22.58%	Set standards (marketing and advertising plus technical)	Technical
7	6	19.35%	Address poverty, equity, and vulnerability	Economic
7	6	19.35%	Promote interoperability and upgrades	Technical
7	6	19.35%	Redirect efforts to other policy areas	Political
8	5	16.13%	Mandate and ensure consumer benefits	Political

Source: Authors

the very bundled smart home you should be able to go to any of the of the components suppliers to fix it, but I am not sure that will happen." R13 addressed this issue by cautioned about: *"it is questionable whether consumers could navigate redress processes or even know who to contact when something goes wrong, especially dealing with multiple products which interact and are provided by multiple companies."* Whilst R23 linked corporate accountability with the use of AI: "*The other issue is when you get into AI and machine learning. Where you get these huge datasets and rather than anyone looking at it and analyzing it, it is through into a machine. That could be very risky because accountability goes away and the system becomes harder for consumers to challenge it. Because we will reach a point where people cannot even explain the formula.*"

One study in Italy, for example, noted that more than half of the smart home products on sale are offered by start-ups with little strength and brand recognition, often not perceived as sufficiently mature and reliable by consumers [50]. A related concern here was lock in to a particular company's products, with multiple respondents mentioning how some smart home technology could be proprietary, meaning only certain applications would work only with certain brands, trapping people into having less choice. This becomes especially acute when one "inherits" a bundle of smart home technologies when moving into, or purchasing, a new house. R23 warned about these risks: "*Another big barrier is being locked-in, particularly in rental properties. If you move into a house and it has an Apple smart kit and you are bringing with you a Google smart kit and they can't talk to each other, you are in a position where the consumer now has to buy all the Apple stuff."*

The actual cost of smart home technology, surprisingly, was not more frequently mentioned, even though all smart appliances, devices, sensors, and systems cost much, much more than their conventional counterparts. As R12 indicated, "*The most obvious barrier to me is cost. As these are high end products, cost is the single biggest barrier. Many times smart home devices are the most expensive options, therefore people simply do not buy them.*" This theme was also picked up during our retail visits, with one Home Base salesperson commenting that in their opinion, *"Smart home technologies are not much requested nor bought. They are still too expensive for the regular customer."* This statement becomes all the more apparent when one realizes a smart coffee machine we viewed during one of our site visits at John Lewis currently cost £1299.99.

Fear of new technology was mentioned as an additional barrier. R1 noted that even more than privacy, "*fear of the unknown*" is a significant obstacle, given "*the perception users have on smart meters played out in terms of how the press created some fear around smart technologies*." As one salesperson confided during a visit to Peter Jones, *"Only one person has actually been interested in buying a connected washing machine and oven. In general, at least for these appliances, people still prefer the traditional versions."*

Two respondents mentioned social isolation and loneliness as risks, a counterpoint to the social inclusion benefits above. Technology comes to replace actual interaction with humans, and can lead to distress and depression. R6 questioned "*in a society where loneliness is a major case of distress, smart home technology is a cold substitute for actual warm people. Is that ultimately a good thing*?" Smart home technologies could exclude people in two ways: by replacing human communication with virtual communication, and by excluding non-users from new online communities [19].

One person mentioned the potential health concerns. R30 mentioned: "*I think of all these wireless connections we still do not know the long-term health implications. I think it connects to the smart homes because we are probably adding more signals, with unknown health effects.*"

7. Calibrating more sustainable smart home policies

Our respondents did not discuss only benefits and barriers and risks, but also 11 policy changes that need implemented to make smart homes more sustainable. Table 6 offers a summary of these suggested policies. Taken together, these polices would promote more sustainable smart home development and deployment across social, environmental, political, and technical dimensions.

By far the most strongly suggested policy recommendation was the need for better consumer protection, privacy, and data security. This covered many aspects of smart home technologies, from data control and restrictions, to encryption, to clear guidelines for ownership of data, as well as safeguards against hacking and piracy. As R2 noted, "*better data and privacy and consumer confidence … are needed to ensure service providers behave in a way that does not undermine confidence and trust.*" And as R15 concurred, "*stronger consumer protection and regulation is a must, regulation to protect consumers is essential.*"

A second recommendation, given the potential for energy rebounds and waste, relates to ensuring that smart home technologies deliver on improvements in efficiency, emissions reduction, energy consumption, and sustainability. R2 elaborated that "*I am most interested in scripting, how to design hardware, control systems, algorithms, and other factors that push energy downwards. This means smart home technologies are not neutral, cannot be controlled any way they like. We need to make smart tech directional, to design it to explicitly reduce energy. There are a multitude of ways to do that, from building it into the kit, or making it the default, a 'harder' path, to merely allowing people to set controls a certain way, a 'softer' path. The result would be setting constraints on people, smart home technologies allow people to do some things, but it also doesn't allow them to do others.*" R12 added that without scripting, "*until reductions in energy demand or carbon are guaranteed, there is no case for smart energy homes*." Such scripting would perhaps automatically cutoff smart home devices if they exceed a certain threshold in terms of emissions or energy consumption.

Participants suggested the need for stronger regulations for energy services or Internet of Things. To this, R27 mentioned: "*peer-to-peer and service base models need to move away from prescription towards more ethical based regulation, so that you are not dictating the business model, but adhering to principles to treat consumers fairly*". For this to happen, R21 added that companies may need to collaborate with each other as well as consumers: "*I know Wi-Fi and Bluetooth are competing with each other. That is also with LPWAN and LoRa. They are all trying to have their own security standards. So now, we should find a space to standardize coding across the whole spectrum. And you have to consider two sides, developer and consumer, to make the consumer happy with a certain interface where they do not need to buy different products, for different things*". With this in mind, R1 noted: "*Essentially we need policies around improving communication protocols between devices such as easy to use and set ups.*"

Other than these top three policy recommendations, another suggestion was for government to continue to provide research as a platform for innovation and learning. This includes more investment in independent science as well as the sponsoring of pilot studies and trials. As R14 noted, "*creating spaces for different institutions to learn together is important … A Living Lab environment where people can experience changes and companies and research institutions can work with them to figure out how to improve the experience and also fix things that go wrong, seeing which work best, and also maintaining consumer protection, would be ideal … Governments need to create this environment where the sector can learn how to deliver the outcomes society wants, and government can make sure they protect consumers and meet the target.*" R15 added that "*Government plays a critical role in innovation, BEIS in particular has a £500 million innovation program for energy … This innovation money is intended to* support *businesses through the valley of death. Innovation funding and R&D is really important*."

Other participants discussed the need for policy that removes barriers and encourages more open market competition. In their systematic review of the smart homes literature, Marikyan et al. warned that regulation and legal stipulations have fallen behind of innovation, with many gaps in national policy and legislation [19]. To this, R26 linked smart meter with competition: "*If we are thinking about the energy smartness, policies that would allow competitiveness and reduce prescriptiveness are needed. So for example: forcing the rollout of smart meters with in-home displays is wasteful as it introduces a technology, the display, which will most likely be redundant in a few years*".

The provision of reliable information and knowledge was articulated as another recommendation, including material printed or online. As R15 explained, "*Sharing knowledge and evidence is key. Industry has knowledge but it's always hard to get out. Government is needed to make strong data and evidence publicly available to all.*"

This suggestion was followed by setting standards—across a variety of domains, including technology as well as advertising and marketing. This, too, covered many aspects of smart home technologies, from better standards for installers and technology providers, to guidelines for consumers, to advertising efforts and better labeling. In terms of advertising, R12 suggested that "*energy efficiency labels should be made and applied to all smart home devices, like the rating scheme we have for lighting or boilers, to ensure the environmental benefits are clear*." R15 mentioned that "*Standards can allow smart controls to be a requirement.*" Hargreaves and Wilson suggest creating national systems of independent certification schemes for smart home technology assessors, installers, and finance providers [34].

Furthermore, protections need in place to avoid a "digital divide" and ensure that smart home technologies do not aggravate poverty and vulnerability. R12 emphasized that "*we must make sure that vulnerable groups are not excluded from any smart home revolution so that no one is left behind. We can tailor literacy, training, and learning, so that those unfamiliar and excluded can come to feel confident and comfortable, or also enhance the welfare of those who cannot afford smart home systems*." R14 agreed and stated that "*smart home technologies will not meet social objectives like tackling fuel poverty or decarbonizing without government intervention and strong policy*." Hargreaves and Wilson already warn that lower income households, the elderly, or those in rural areas with poor internet access are later adopters of smart home technologies [34]. Grants, subsidies, and free technical advice could be targeted at these groups, as well as efforts to improve high-speed internet access.

The promotion of required interoperability and upgrades is yet another vital area for government. Hargreaves and Wilson note that clear national policy guidelines can ensure hardware and software is compatible not only within the home, but also with communications portals as well as energy suppliers or system operators, especially during periods of peak usage [34]. Both R8 and R23 commented on tackling interoperability to benefit consumers and avoid been locked-in. Respectively, they noted: "*Interoperability needs to be addressed. Smart ecosystems have to play well with each other … so users are not trapped in a particular system*". R27 echoed this concern: "*We need central policies on business converging on standards for interoperability to avoid misspending capital … I think these technologies should be interoperable by default.*"

Redirecting efforts to other policy areas underscores that we should not place all of our bets on smart technology. Or, in other words, that we also continue to invest in other measures, such as energy efficiency, passive design of infrastructure, or fuel poverty, in tandem with smart investments. As R6 explained, "*I am not sure I actually want policies to accelerate smart homes until we tackle other problems. Here in the UK, we have a real, enormous and serious problem of homelessness, all the hidden homeless alongside those on the streets. Among the homes we have, 8 million could do with getting loft insulation for the first time or topped up to a decent level. We have an enormous amount of work to make homes more livable, getting energy demand down from those, and eradicating fuel poverty. If you really want to improve lives, lessen the environmental impact of our energy system, and create jobs, you don't want to focus on smart, you want to focus on ordinary energy efficiency upgrades, such as retrofits and refurbishments. We have so much policy attention on smart home technologies, but so few on creating decent social housing for the chronically poor.*" R9 estimated that "*turning the temperature down 1 degrees saves £75 a year, you don't need smart tech to do that!*" As Fig. 7 suggests, more annual savings for households can occur in the UK from investments in efficient boilers, insulation, and windows than smart controls or behavioral change from smart meters.

Mandating and ensuring consumer benefits came next as a policy suggestion. As R25 noted: "*policies are not designed with 'me' in mind, they are designed with the system in mind. So principle number one needs to be to think about what it looks like from the consumers' perspective, would it persuade consumers to do what we want them to do? Too much data flows from the consumer but very few rewards flow to consumers. Policy must correct that.*"

8. An agenda for future smart homes research

Notwithstanding the findings from our study concerning benefits, barriers and risks, and policies, we also believe it points towards three areas of future research.

8.1. The demographics and practices of early adopters

The first, and perhaps most obvious, is that we need more research of actual smart home users and adopters, those with direct experience of the technologies, rather than work on the more common general public opinions and perceptions. Studies of some early adopters suggest that they share complex characteristics not representative of the national population. In the United Kingdom, for instance, trials of smart heating controls suggest that the youngest age of users (18–35 years old) were most satisfied and able to perform the most tasks; those 55 years old and above were significantly less satisfied, as were those with a physical disability [51]. In Israel, smart home technology was similarly more favored by the young, with smaller families or households, who did not consider themselves religious [2]. In Australia, participants in a smart homes trial tended to be 25 years or older as well as high income earners [60]. Interestingly, according to Jensen et al. [60] such smart home users could be described according to three archetypes or personas. The *helper* sought to keep devices on all the time to assist with tasks and thus led at times to increased energy or lighting demands. The *optimizer* focused attention on smaller actions (e.g. turning lights off) and sought

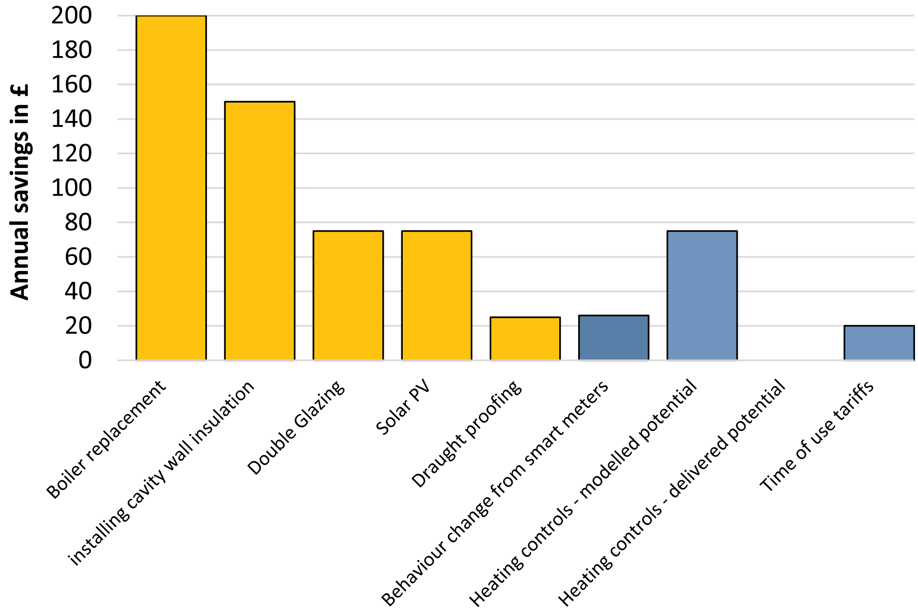

Fig. 7. Monetary savings from different home energy efficiency options in the United Kingdom, 2018.
Source: Authors, based on data from the Energy Savings Trust.

the energy efficiency benefits of devices. The *hedonist* was more playful and utilized smart home devices to create aesthetically pleasing and fun living spaces. Several recent papers have called for developing a better picture of who smart homes users are, and a better understanding of how smart home technologies are used in practice, looking at the relationships between smart technology and its users, and consideration of the purpose of smart homes [20,21,43,61].

This connects in part to the issue of energy rebounds and waste. Horner et al. [62] suggest that while the technical potential of net energy savings from ICT is "likely positive", the magnitude and even sign of real savings is unclear and difficult to assess, depending on user interaction and broader societal impacts. They suggest that empirical studies are needed to gather more data on how ICT systems are actually deployed and used in practice, in order to better identify the parameters driving energy use in ICT-heavy systems. This knowledge would help avoid a situation where smart home technologies are developed and sold based on poor or misleading information [43]. Both R16 and R22 cautioned on this issue, respectively they noted: "*You can have a huge rebound effect. When you look at the number of connected devices and we're now into millions in the market, every single one of those consume a little bit of power all the time when they are connected. When you add it up, you get millions of devices that are all consuming electricity just to be connected*" and "*smart homes could be a double edged sword, there is no clear evidence if this is going to reduce demand*".

Moreover, incomplete information has been highlighted in criticism that the smart home industry and its vision creators are overwhelmingly male [1], and that the "smart technology agenda" focuses on a "masculine ideal consumer," suggesting more consideration of the gendered roles in everyday life is necessary for a successful transition to a future of smart homes [20]. Furthermore, articles about smart homes are often authored by people associated with the industry, who are advocating smart technologies, even representing industry visions of how everyday practices "should" change [1].

8.2. The duality of control

Much of the smart home technology narrative circulates around the notion of "control," as Fig. 8 illustrates, but we suggest this notion needs further unpacked and contextualized. R22 remarked that "*smart homes open a very interesting debate about control and to use a popular political phrase of recent times, all these technologies are being sold on the grounds of taking back control. But, if we look carefully, a lot of control might be taken away from people.*"

Fig. 8. A Curry's PC World advertisement for smart homes centering on "control," London, November 2018.
Source: Authors

For instance, there seems to be a duality of meaning about smart control that actually conflicts with itself. The first notion of control involves informing and empowering consumers to make better "energy choices," and enabling smart technologies to act with minimum consumer participation [57], epitomized by efforts from the Low Carbon Innovation Coordination Group [63] or the European Union Smart Grids Task Force [64]. The second suggests that smart technologies would work better by "circumventing" users to optimize energy use. Chen et al. [65] epitomize this view by framing smart home systems as an intelligent "butler" acting both to reduce energy use and peak load, but also predicting user demands and managing smart appliances as "servants."

This dichotomous representation of control however can be criticized, as the first presents an informed consumer as an unrealistic automaton [66], while trials suggest users limit themselves to the more basic functions of SHTs [43]. The second implies an indifferent consumer, leaving no room for an engaged citizen; this approach could miss opportunities for domestic energy savings through demand side management [66]. A more fruitful conceptualization of control comes from Hargreaves and Wilson, who suggest in Table 7 that it can include objects, loci, and distinct implications for sustainability, as well as different types of control: technological (which they call "artifactual"), perceptual, and relational [34]. Technological control refers to the actual, physical ability to use or program technologies, but perceptual control relates to more diffuse and difficult attempts to control consumption patterns or even emotions, and relational control expands this over an entire lifestyle or household identity. The implication is that we need further research on how various types of control can clash and create a paradox where some increases in control, say technological, can erode and diminish feelings of perceptual or relational control, overwhelming adopters.

8.3. Beyond smart homes to socio-technical systems, practices, and justice

A final theme we suggest exploring is to decenter the home in the analysis of smart home technologies, and to expand it to look at (a) the socio-technical system of smart at other scales including cities, states, and even regions; (b) practices; and (c) equity, inclusion, and justice.

R12 made this point about a systems focus explicitly, suggesting that: "*There is an important agenda to expand smart home research beyond feedback, from beyond a device like a smart meter, to the whole home, then to smart grids and smart cities and a smart planet. The notion of smart operates across a variety of scales*." Expanding the unit of analysis from homes to systems would remind us that smart home technologies also involve global organizations, institutional rule systems and structures, and cultural values. This demands a shift in focus from individual technologies to the broader scope of "systems of systems [67]." R25 added: "*We need to get away from the obsession we have in policy terms of supporting a technology … we need to think about the home as part of the system.*"

An array of specific socio-technical approaches could be well suited to expand the conceptual repertoire of theoretical frameworks used to understand smart homes. As Table 8 indicates, the Multi-Level Perspective (MLP) analyzes socio-technical transitions by emphasizing regimes, dominant routines, and alternative spaces or niches. Actor Network Theory (ANT) invokes concepts such as "network assemblages" and "sociotechnical imbroglios" to focus on agency or politics, especially at the micro level. The Social Construction of Technology (SCOT) emphasizes closure, frames, and the meaning groups of stakeholders give to technology. Technological Innovation Systems (TIS) do assess complexity and variation in large systems, but prioritize the functional aspects of innovation. Large Technical Systems approaches underscore the role of system builders as well as how path dependence becomes embedded.

Novel approaches to smart homes do not necessarily need limited to socio-technical systems. Social Practice Theory – also called by some

Table 8
Five socio-technical conceptual approaches relevant for smart home technologies.

Theory/ concept	Discipline(s)	Application to smart home technologies	Key concepts
Multi-Level Perspective (MLP)	Evolutionary economics, sociology, innovation studies, STS	Transitions: socio-technical system change behind smart homes	Niches, regimes, and landscapes
Actor Network Theory (ANT)	Sociology, STS	Agency: how actors (human and non-human) build and become entangled in actor-networks	Network assemblages, translation, enrollment, entanglements, politics
Social Construction of Technology (SCOT)	STS, history of technology	Meaning: how different groups of social actors interpret smart home devices, systems or services	Interpretive flexibility, relevant social groups, technological frame, closure, heterogeneous engineering
Technological Innovation Systems (TIS)	Innovation studies	Innovation: the interconnected functions that promote or future smart home development	Knowledge development and diffusion, entrepreneurial experimentation, broader political and social influence, market formation, legitimation, resources mobilization, positive externalities
Large Technical Systems (LTS)	History of technology	Systems: Large-scale, capital intensive socio-material systems and sub-systems; how system builders develop smart homes and embed them into society	System-builders, momentum, reverse salient, load factor, vertical and horizontal coupling

Source: Authors modified from Ref. [68].

Table 7
Objects, loci, and implications of "control" for smart home technologies.

	Technological	Perceptual	Relational
Object of control	Technologies, devices	Perceptions, feelings	Everyday lives, activities, relationships
Locus of control	Smart technologies	Users	Relationships between people and activities
Core assumptions	More control over more devices is better	People want to feel in control	People desire control over their domestic lives
Implications for sustainability	Smart homes should lead to energy demand reduction through rational management	Smart homes may lead to demand reduction if users feel '"in control," but may also have little or negative impact if users feel out of control	Smart homes may lead to demand reduction, but may also generate more energy-intensive lives

Source: Modified from Ref. [34].

"theories of practice" – seeks to reveal the beliefs, values, lifestyles and tastes that express personal choice behind behavior [69]. At its heart sits the notion of a "practice," a type of behavior that is routinized much as is a habit, but that also links together bodily activity, mental activity, and things and their uses [70]. Social practice theorists [71–73] have tended to argue that a practice approach emphasizes four things, which can certainly be applied to smart home technologies. Materials or *materiality* encompasses the technologies, tangible physical entities and other things that make up material objects of a smart home. *Competencies* would reflect the skills, habits, knowledge, tacit knowledge and technique needed to utilize smart home technologies or services. *Meanings* would capture the ideas, symbolism, aspirations, and other cognitive dimensions attributed to or associated with smart homes. *Connections* would describe how certain practices for smart homes emerge, persist, shift, or disappear over time. Indeed, multiple respondents discussed how smart homes could lead to an extension or transformation of practices. R21 mentioned the possibility that "*smart technologies can automatically recognize behaviors and changes in the environment based on the use of preferences and perform on predefined routes to act*," whereas R28 commented that smart homes could be instrumental in aiding an "*understanding of user routines*" as well as "*pro-environmental behaviors*." The strength to this approach is that it would also, similar to socio-technical transitions theory, de-centre the smart home in analysis and better describe how processes of change are integrated with social processes and very often mundane everyday shared conventions of living, doing and working [70].

Finally, justice or equity centered frameworks would ask analysts to regard smart home technology and systems as more than simply hardware, as beyond a black box, and instead in moral or judgmental terms. In other words, these approaches would reframe or re-politicize what smart home technologies are [70]. Smart home technologies can be seen through this lens as possible mechanisms of resource extraction that transfer wealth from developing countries to developed ones, or systems of segregation that separate negative harms from the positive attributes across different classes of consumers. As R13 warned, smart homes could give rise to serious "*distributional impacts … if people are unable to access these technologies … these people might be excluded from these technologies and we need to bring them along to this journey or at least offer them some protection*". A similar point was brought by R31, who stated: "*The energy market is about to become a lot more complicated and that is something were the analogue energy market absolutely failed at doing, which was protecting the most vulnerable people and that is something that the smart energy market obviously must do.*" Thus, smart home technologies can potentially concentrate political power, facilitate inequality or vulnerability, or validate unfair or elitist patterns of smart home diffusion, which make them well suited to examine from an explicit equity and justice lens.

9. Conclusion

In sum, for consumers at least here in Europe and the UK, the smart home revolution is upon us. We documented a sobering 267 smart home technology options available to consumers today, provided by 113 different companies and available from a multitude of direct suppliers, home improvement stores, general department stores, and electronics and appliance retail shops. This array of options ranges from devices that can merely create isolated or bundled smart services, at lower levels of the smart spectrum, all the way towards more automated, intuitive, and sentiment options such as artificial intelligence, robots, and drones.

Whether users will adopt and embrace this motley collection of devices, however, is uncertain, all the more so since adoption is a complex process that cuts across many of the dimensions we examined in this study. For instance, the evidence we collected across our expert interviews, site visits, and academic literature suggests that, among other things:

- Concerns about privacy, security, and hacking must be addressed;
- Smart home technology must operate reliability and intuitively, with strong warranties and built in longevity;
- Users will not just magically absorb new technologies into their homes and lifestyles, instead learning and acceptance need to occur;
- Efforts must be made to ensure markets for the technology remain open and transparent, and threats to democracy and surveillance capitalism identified and managed;
- Interoperability needs assured across multiple levels, including between non-smart and smart devices, smart devices and each other, and smart devices and different systems across various suppliers and layered infrastructures (such as electricity, heat, internet, and so on);
- Energy rebounds and wasteful consumption must be reduced, perhaps through better standards, information to users, or even built in "scripts" that shut off devices that lead to excessive consumption or carbon emissions;
- Similarly, material inputs and the backside of the digital economy need managed sustainably, especially flows of electronic waste and the energy needed for data centers and ICT;
- Interventions need targeted to ensure a digital divide does not worsen and that poor, vulnerable, or otherwise excluded groups can benefit fully from emerging smart home options.

This laundry list of suggestions mirrors those made in some of the literature. Balta-Ozkan et al. suggest that user acceptance of smart home technologies must meet *five* different dimensions (which intersect with some of our other identified barriers): fitting with lifestyles, being easy to use and administer, being interoperable with existing homes, being perceived as reliable, and being perceived as safe [74]. Wilson and Hargreaves also argue that "smartness" must be promoted but only in ways congruent to perceptions of the home, and the values and identities of its occupants [20].

One implication is that given widespread diffusion of smart home technologies rests on such a complex confluence of factors, it may continue to occur in isolated bits of technology rather than across multiple bundled systems. Another implication is that not all smart home devices meet sustainability goals, and that for the technology to have transformative impacts on reducing energy demand—or, even just incremental reductions in demand—the sector needs strongly guided by government and policy. Such policies at the moment appear to occur in a fragmented manner across different silos such as smart meters, smart grids, or the Internet of Things. Instead, our evidence strongly suggests we need an integrated set of smart homes policies that not only protect consumers but also set restrictions to ensure such devices meet other climate and energy goals (such as fuel poverty or efficiency), sponsor innovation and trials for learning, and set technical and marketing standards. Even then, future research ought to focus more on the experiences of actual adopters, expand notions of control, and begin to focus on smart systems of systems, or bundles of practices, rather than just individual discrete homes.

Perhaps then, with a more thoughtful and coordinated mix of policies in place, and research attuned to more nuanced, independent, and dispassionate dimensions of smart home technologies, their adoption will begin to fulfill some of the objectives their advocates continually promise.

Declaration of competing interest

None of the authors have any formal conflicts of interest to declare.

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Appendix A

Appendix I. Definitions of smart home technologies by expert respondents (n = 31)

#	Definition
R1	There is a range of different smart devices, but the distinguishing factors that make them smart are system functionality and how their systems communicate and operate.
R2	SHTs are a diverse constellation of technologies which provide households with greater controllability over a variety of domestic systems, processes and services. This can range from heating and lighting to electricity use and appliances, to security, safety, and so forth.
R3	Smart home technologies are intelligent operating systems which allow users to operate different parts of the house, the environment and ambient. With the goal of easing the life of users.
R4	Smart home technologies are eclectic products that are installed at homes through internet or external networks connected. They are everyday objects enabled by smart services that should do more than they could do before.
R5	Smart home technologies are devices that are able to make decisions; thus the smartness. These devices should be able to make those decisions based on users' behaviors, commands and preferences.
R6	I see two categories of smart home technologies. The first, is the smart home with an emphasis on what happens in the home; there are sensors around the place and could be remotely controlled. The key elements in this category are "switching and sensing," with what used to be the province of human beings in the home getting delegated to the technology. The second category, is how smart technology changes the boundaries of the home by bringing the Information Technology (IT) into the electricity system. Here, the key word is "Connectivity" and should provide users with the possibility of changing local network operation as the result of what happens in the home
R7	Smart home technology is any device that helps the user to do certain tasks more efficiently; whether these tasks are related to security, improving the energy efficiency of the house or by adjusting to users' daily routines. So basically, anything that is useful for the user and connected from (IoT).
R8	Smart homes are an extension of an everyday technology. There is an implication that it is digital. If a smart home is digital, then it has the ability to learn and adapt to people and extend the capabilities of people.
R9	Smart home technologies are internet connected technologies which can monitor or control aspects of the home.
R10	Smart home technologies are devices within the home that possess network connectivity. Hence, are able to cooperate through computation to enable things to happen with all the other connected devices in the home.
R11	Smart home technologies are everyday objects and devices that connect to the internet and to each other; not computers, smartphones, or tablets. Smart devices often connect to apps on mobile devices, allowing users to control them remotely.
R12	Smart homes should use information and communication technologies to enhance domestic life. In this sense, a truly smart home is the one which uses ICT through the use of interactive settings and feedback on the domestic environment.
R13	Smart home technologies are internet enabled devices that respond to signals. These could range from price signals to DNR signals.
R14	Smart can refer to how we can use the latest technology. Smart could also encompass ways of thinking, techniques and approaches. However, true smart, is about combining humans with technology to perform activities more effectively, about human software and technological hardware
R15	Smart home technologies are digitally enabled devices that provide opportunities to manage energy better. Where the digital component is key. Currently lots of things are called "smart" but are meaningless, it generally means moving from analogue to digital.
R16	Smart home technologies are connected interfaces or appliances within buildings that can be used to improve energy management.
R17	Smart home technologies need to have a learning algorithm through a machine that is connected to the internet and can do things like predictive maintenance or predictive behavior to better manage cooling and heating within buildings
R18	A product or service that reacts to data either related to the households or external information, such as energy prices.
R19	Products or services that involve connectivity, digitalisation and automation. These could apply to energy use, lightning, electricity or gas.
R20	Smart homes technologies typically require a digital intermediary that is connected to the internet and a set of hardware which is by design insecure and not updatable. What smart homes could do, is to automatically manage your energy and automatically configure itself in order to provide the service that the user wants. Smart homes should use energy and –potentially water– as efficiently, effectively, flexibly and as simple as possible.
R21	Smart home technologies are devices that automatically recognize the behavior and changes in the environment based on the use of preferences and act on predefine routes to do something. As a result, users do not need to program them anymore. These technologies' main goals are to improve the energy utilization, comfort and safety of the home.
R22	Smart home technology is whatever the company is telling consumers about what it is manufacturing. Hence, it is usually presented as what kit/technology the manufacturer has in their portfolio. A smart home should give users a lot of energy services, for little energy use
R23	Smart home technologies is anything that is using data above and beyond of what that piece of kit might usually do. Any device that enables that service.
R24	Smart home technologies are everyday domestic objects that are networked to other technologies.
R25	Smart home technologies are devices that improve the energy service delivered to the consumer and/or maintaining whilst delivering a service to the system. There are two different types of smart technologies. One type, assumes virtually no interaction with the consumer and they will only become widespread if are accepted and adopted by consumers. The second type, consists an additional functionality for the user.
R26	Smart home technologies are pieces of kits; whether a hardware or software that allow someone who lives or stays in the home to control features related to energy. Either the user controls it or delegates control to a system. The system could be within the home or it could be a national, regional or an international system where the smart component aims at enhancing the system.
R27	Smart home technologies are connected devices in one form or another that provide a service that uses available data in a new way. The smartness comes from been able to interpret the data available by an algorithm that brings useful elements in one way or another. The "smartness" comes from recognizing what is unusual behavior and behavior that should brought to the attention of someone.
R28	Smart home technologies are devices that collect data and send it back to the consumers through different channels of communication, could be through a text message, call, voice, emails or displayed on websites. Smart home technologies should also be able to be controlled remotely and provide users with the ability to stay close to the appliances without been physically there. These technologies should also be able to be programmed to provide more comfort to users. I see them as a as a platform of information in which users can be coached whilst delivering better services to the population.
R29	A smart home should allow users to control the energy load in the house by looking at vectors in the following order: heat, motion, lightning and communication. Controlling those in a manner responsive to three elements: the first been commercial signals, essentially energy prices; the second is the ability to deliver the energy requirements to the home in a commercially efficient manner, so it is closely associated to automation; and third, it is responsive not only to commercial signals, but to ambient-environmental signals.
R30	The use of ICT on how we control and manage our homes. The utilization of ICT by various apps and other technologies to control and manage our homes more intelligently. So it could be linked to energy or not.
R31	Smart home technology is a lifestyle opportunity that enables users to make things simpler and easier whilst improving lifestyles. However, the smartness goes beyond technology, it also entails data services which sit around and are overlooked behind the infrastructure.

Source: Authors

Appendix II. 267 available smart home options

This appendix is in Microsoft Excel format and is uploaded as Supplementary Online Material (SOM) available at the hyperlink at the end of the manuscript.

Appendix III. Availability of smart home technology options across 39 site visits in the United Kingdom, January to February 2019

Shop Visit	Appliances	Lighting	Energy, gas and utility	Entertainment	Health and wellness	Safety and security	Integrated solutions	Vehicles and drones	Home robots	Baby and pet monitors	Gardening	Clothes and accessories	Others
1		x											
2						x							
3	x	x	x	x	x	x	x		x			x	
4		x	x	x		x	x					x	
5	x	x	x	x	x	x	x					x	
6		x	x	x	x	x	x			x		x	
7		x	x										
8						x							
9						x							
10	x	x	x	x	x	x	x					x	
11		x	x	x	x	x	x	x	x		x	x	x
12				x								x	x
13		x	x	x	x	x	x			x		x	
14				x	x					x			
15	x	x	x	x		x	x					x	
16						x	x					x	x
17				x			x						
18		x	x	x	x	x	x	x	x		x	x	x
19	x	x	x	x	x	x	x		x			x	
20						x	x					x	x
21		x	x	x	x	x	x	x	x			x	x
22	x	x	x	x		x	x	x		x		x	
23						x							
24		x	x	x		x	x					x	
25				x			x					x	
26		x	x	x	x	x	x	x	x		x	x	x
27						x	x					x	x
28		x	x	x		x	x					x	
29		x	x	x		x	x					x	
30		x	x	x	x	x	x	x	x		x	x	x
31				x			x					x	
32		x	x	x	x	x	x		x	x		x	
33		x		x		x	x					x	
34							x					x	
35		x	x	x	x	x	x	x	x		x	x	x
36						x							
37						x							

Frequency counts:

Rank	Frequency (availability by shop visit)		Class of smart home technology
1	29	78.38%	Safety and security
2	27	72.97%	Smart home solutions
2	27	72.97%	Clothes and accessories
3	25	67.57%	Entertainment
4	22	59.46%	Lighting
5	20	54.05%	Energy, gas and utility
6	14	37.84%	Health and wellness
7	10	27.03%	Others
8	9	24.32%	Home robots
9	7	18.92%	Vehicles and drones
10	6	16.22%	Appliances
11	5	13.51%	Baby and pet monitors
11	5	13.51%	Gardening

Source: Authors

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2019.109663.

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