



Smart home technology adoption in Denmark: Diffusion, social differences, and energy consumption

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Abstract Smart home technology (SHT) is increasingly entering homes to provide services such as energy management, security, comfort, and convenience. However, research shows that adoption varies across social groups and that SHT might affect energy demand. Denmark is considered a frontrunner in the uptake of SHT and offers a unique opportunity to combine administrative household information with energy consumption data and survey responses on SHT uptake. This paper studies a representative sample of 1,468 Danish households to investigate SHT diffusion, social differences in SHT adoption, and correlations between SHT and energy consumption, divided into appliance use and heating. The results indicate that entertainment and home security are the most popular SHT services in Denmark and that SHT

is more widespread among younger households, especially for entertainment and robotic help. In contrast, smart heating systems are more widespread among older households. Living in a detached house seems to increase the likelihood of having SHT, while the highest income group appears more likely to have security systems, and technical education seems associated with the adoption of SHT for heating management. Finally, smart security systems were associated with higher electricity consumption, and SHT for electricity management was associated with higher heating consumption and to a lesser extent higher electricity consumption, but there was no significant correlation between having smart heating control and heating consumption.

Keywords Smart home technology · Smart heating · Energy demand · Electricity consumption · Energy services · Technology adoption

Highlights

- Entertainment and home security appear to be the most in-demand SHT services.
- Younger households and households in detached houses seem more likely to adopt SHT.
- Technically educated people seem more likely to have SHT for heating management.
- SHT services of security and electricity management, e.g., smart lighting, link to higher electricity and heating demand.
- Smart heating management does not seem to reduce heating consumption.

Introduction

In recent years, smart home technologies (SHT) have been increasingly entering the domestic sphere. Although previously designed for luxury homes (Darby, 2018; Gram-Hanssen & Darby, 2018), a range of SHTs are now designed for ordinary everyday activities such as cleaning and cooking (Aagaard, 2022). Defined as internet-connected technologies to provide services within the domestic sphere,

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and to the energy system (Gram-Hanssen & Darby, 2018), SHT covers many everyday practices, devices, and services, yet it seems difficult to live up to the underlying expectations related to energy efficiency, comfort, convenience, and controllability, etc. (Hargreaves et al., 2018; Strengers & Nicholls, 2017). The optimistic potential of SHT seems to originate in its initial purpose of being designed for luxurious and convenient living (Darby, 2018) with industry visions of *passive* users (Aagaard, 2021), and when implemented in *mundane*, *dynamic*, and *complex* everyday practices, these promises risk becoming disruptive and inconvenient elements of everyday life (Hargreaves et al., 2017a), for example by necessitating ‘workarounds’ to accommodate the technology in routine everyday practices (Larsen & Gram-Hanssen, 2020).

Diffusion of SHT is thought to be key to achieving energy efficiency, and energy reductions, and generally contributing to decarbonization and future energy transitions (Li et al., 2021; Sovacool & Furszyfer Del Rio, 2020). Moreover, SHT plays a key role in visions of smart grids and smart cities (Lund et al., 2017), and the research interest in smart home adoption appears to be increasing (Li et al., 2021).

Although the SHT diffusion rate has been described as low (Marikyan et al., 2019) and SHT might not be perceived as mainstream (Chang & Nam, 2021), the SHT market appears to be expanding (Sovacool & Furszyfer Del Rio, 2020). According to Eurostat data from 2022 (ISOC_IOT_USE), around 10% of European households have SHT¹ in the form of home appliances such as robotic vacuum cleaners, home security systems, and energy management systems. This percentage is higher for Danish households than the European average, with 20% having smart home appliances, 17% with home security systems, and 15% with energy management systems. According to the Eurostat survey, 55% of households across EU countries have smart TVs, the most widespread SHT, while this figure is 66% in Denmark. Denmark can therefore be considered among the frontrunner nations when it comes to the uptake of SHT, alongside Norway and the Netherlands. However, this seems to be a rather recent trend. Based

on survey data conducted by Statistics Denmark, the adoption of smart TVs increased from 40% in 2015 to 70% in 2021, robotic vacuum cleaners increased from 9% in 2015 to 12% in 2021, and intelligent control of heating or electricity increased from 16% in 2020 to 22% in 2021 (Hohnen & Hansen, 2022). This indicates that the popularity of smart technologies has increased recently, although, from an energy consumption perspective, the adoption of smart heating control appears as the most interesting increase, often as part of home energy management systems (HEMS) (Mahapatra & Nayyar, 2022).

Whether SHT is expected to improve efficient and flexible energy use, underpinning convenient and comfortable everyday living, or improve health, safety, and entertainment in future homes, the diffusion across various types of households and the impact on household energy consumption are important topics to investigate.

This paper investigates the research questions: *which* households tend to acquire SHT and *what* impact do these technologies have on their energy consumption? This is investigated using data from a representative survey of 1,468 Danish households in combination with administrative data.

This paper thereby addresses three aspects of SHT adoption: the diffusion of SHT across types of appliances and services, the differences in adoption of SHT across socio-demographic groups, and the relationship between SHT and energy consumption. The situation in Denmark offers a unique opportunity to combine survey data with energy consumption data and register data. The register data comes from administrative records, where information on socio-economics and housing for all people living in Denmark are registered using a unique identification number.

This data allowed analysis of diffusion, differences in uptake, and the relationship with energy consumption for the same sample of households. However, the case of Denmark and the use of survey data limit the study to investigate the smart appliances that were asked for in the survey and to a certain extent to the context of a prosperous Nordic welfare society.

Despite the limitations, the analysis contributes new evidence on SHT adoption in three ways. First, rather than investigating intentions to buy, awareness of products, or specific preferences, the variables indicate ownership of SHT, which reflects actual

¹ In the Eurostat survey, SHT is referred to as Internet of Things (IoT).

purchases. Although the data are self-reported, this can contribute to better evidence of which households tend to acquire SHT. Second, despite minor biases, the survey sample is representative of the total population in Denmark. This means that the analysis reflects ‘ordinary’ households rather than the likely biased samples in pilot studies or trials. Thus, the sample might reflect what Rogers (2010) describes as an early majority, which follows the stage of early adopters. Third, the analysis is based on more extensive data than previous studies based on surveys (e.g., Arthanat et al., 2019, 2020; Parag & Butbul, 2018; Sanguinetti et al., 2018a, 2018b; Shin et al., 2018) in terms of the number of observations and variables. This is also one of the first studies to specifically investigate the Nordic region.

Definition, diffusion, and adoption of smart home technology

To give a background for this study, this section presents relevant literature on the definition, diffusion, and adoption of SHT. It may not be clear exactly what the term SHT refers to. When defining SHT, three features seem to recur. The first feature is the *connectedness* of devices. To communicate, technologies must be digitally connected in some way, for example being integrated into systems or networks, including the Internet of Things (IoT). In particular, information technology such as smartphones, sensors, touchscreen panels, or digital voice assistants like Google Home and Amazon Alexa is important for devices to connect with lights, heating systems, and other domestic appliances (Tirado Herrero et al., 2018). This also includes how a technology is set up to control, monitor, or communicate with another device, for example, to anticipate and respond in certain ways (Aldrich, 2003).

The second feature is the *residential* location. This simply means that SHT, or the services provided, are located within the domestic sphere and residential housing, but can be controlled by residents or others outside the home (Gram-Hanssen & Darby, 2018).

The third feature is the *services* that SHT provides or is expected to provide. Combining the four features, SHT refers to the automation of connected technologies aimed at providing services within the domestic sphere or as Furszyfer Del Rio (2022)

defines it: SHT refers to “[...] appliances that need to be digitally connected, provide some degree of automation and deliver enhanced services to occupants”. When considering SHT as a part of smart grids, the complex communication networks and remote monitoring may also provide services to electricity system operators (Gram-Hanssen & Darby, 2018), for example, the technical potential to deliver energy saving or time-shifting of energy demand (Ford et al., 2017).

Previous literature mentions a list of services related to SHT. Services related to energy demand are among the most well-described (Li et al., 2021), for example in terms of savings, flexibility, and control of energy demand, including electricity use, heating, and cooling (Darby, 2018; Shin et al., 2018; Sovacool & Furszyfer Del Rio, 2020). Services related to SHT also include safety and security (Shin et al., 2018), convenience, controllability, and comfort (Strengers, 2013; Strengers & Nicholls, 2017), entertainment and enjoyment, as well as more generally financial benefits, aesthetics, functionality and privacy (Sovacool & Furszyfer Del Rio, 2020). Finally, SHT can also symbolize wealth or a commitment to sustainability (Schill et al., 2019).

This variety of services reflects how the diffusion of SHT holds many promises (Skjølsvold et al., 2015; Sovacool & Furszyfer Del Rio, 2020; Strengers & Nicholls, 2017). The technology industry seems to promote visions of increasing levels of comfort and convenience for (passive) users (Aagaard, 2021; Strengers & Nicholls, 2017), whereas energy policy seems to envision SHT as a tool to provide energy efficiency and flexible energy use (Strengers & Nicholls, 2017). For example, the European Directive on energy efficiency in force (European Parliament 2018) incites member states to promote smart technologies (Article 2a) using a smart readiness indicator to measure a building’s capacity to use information and communication technologies to accommodate the needs of occupants and the energy grid (European Parliament Directive, 2018, recital 30). However, Jauhunen et al. (2019) argue that cold-climate buildings do not fit well with the smart readiness indicator, as it is defined in the EU directive.

SHT requires adaptation and familiarization from householders (Hargreaves et al., 2017a), which might lead to an initial interest in functionalities, but if the practical benefits are not clear, SHT risks being perceived as gimmicky and unnecessary (Sanguinetti

et al., 2018a, 2018b). SHT may also increase household labor (Strengers & Nicholls, 2017) and lead to unequal gender roles (Aagaard & Madsen, 2022; Furszyfer Del Rio et al., 2021), while its implementation relies on specific (technical) competencies (Aagaard et al., 2023; Larsen & Gram-Hanssen, 2020; Madsen et al., 2023). In addition, SHT might contribute to increasing levels of energy consumption (Darby, 2018; Hargreaves et al., 2017b; Peffer et al., 2011; Strengers & Nicholls, 2017), yet the direct effect of SHT on electricity or heating consumption is still unclear.

Several studies have described the adoption of SHT using the theory of diffusion of innovation by Everett M. Rogers (2010). Following this theory, SHT adoption can be described in five steps representing different groups of technology adopters (from innovators to early adopters, early majority, late majority, and laggards). Pantzar (1997) presents an alternative to Rogers' diffusion of innovation theory by focusing on how SHT adoption can be seen as a process of domestication of everyday life technologies. This follows three steps, where SHT starts as fashionable objects of desire, then becomes objects that are reasonable to acquire in terms of functionality, and finally, objects of routine, where acquisition is ordinary and requires no justification (Pantzar, 1997). The element of domestication in SHT adoption links to studies on the smart home. Hargreaves and Wilson (2017) distinguish between three views on the smart home (functional, instrumental, and socio-technical), and Hargreaves et al. (2018) outline four distinct motivations to adopt smart home products: 1) saving energy, 2) interest in new technology, 3) protecting the environment, and 4) a desire for improved control. Moreover, Gram-Hanssen and Darby (2018) describe four perceptions of a (smart) home: 1) a controlled and secure space, 2) a site of activity and practices, 3) a place of relationships and continuity, and 4) an expression of identity and values. These studies emphasize how existing dynamics in the home, for example, related to aspects of functionality, control, and social relations, are important in the adoption and implementation of SHT. In a similar vein, Madsen et al. (2023) show how three ways of approaching and implementing SHT in everyday practices (i.e., the critical, the compliant, and the committed) represent embodied competencies acquired through previous practice and experience.

Sovacool and Furszyfer Del Rio (2020) point out social differences in the adoption of SHT as an important topic for future studies. However, from previous studies, there is already some knowledge on this. A general finding is that the adoption of SHT tends to reflect economic and technological developments, with a following bias towards urban areas and developed countries (Tetteh & Amponsah, 2020). Focusing on specific contexts, a review of socio-demographic variations in SHT adoption shows some clear differences across different socio-demographic groups. SHT adoption seems to be correlated with a higher income (Sanguinetti et al., 2018a, 2018b; Shin et al., 2018) and not living alone (Arthanat et al., 2019). The age of occupants also seems to be an important parameter, where younger households tend to buy and use SHT more than older households, which is reflected in an observed lack of adoption among older households (Arthanat et al., 2019, 2020; Pal et al., 2018). This is in line with an Israeli study finding that SHT was favored by younger households (Parag & Butbul, 2018). On the contrary, a South Korean study found that younger consumers had lower intentions to buy SHT (Shin et al., 2018). Finally, a Danish study indicated that some occupants were not willing to adopt Smart Energy Technologies even when they perceived such technologies as being useful in lowering energy consumption (Billanes & Enevoldsen, 2022).

Although the previous studies reviewed above provide valuable knowledge on the process of adoption of SHT, then more research is needed, not least given the high political expectations of the role of SHT in managing and reducing energy consumption. This study aims to contribute to the existing literature by providing new knowledge on social differences in the adoption of different types of SHT and investigating the impact of SHT on actual energy use. Thus, this paper contributes with empirical evidence on 1) the diffusion of SHT across types of appliances and services, 2) which types of households tend to have different types of SHT, and 3) how having SHT is associated with levels of energy consumption. While the majority of previous studies are based on intentions to buy, we contribute to the existing literature by analyzing survey data with declared purchases combined with energy consumption and administrative register data.

Data, variables, and methods

This section presents the data and variables used in the study and the methods that were used to analyze this data.

Data

The analyses were based on data from a survey among a representative selection of Danes combined with data from Danish registers and data on household electricity and heating consumption (district heating and gas). The survey questionnaire was designed by [Anonymized for peer review], but conducted by Statistics Denmark.

The survey responses were collected during the period November 2020 to January 2021, while the electricity and heat consumption data and register data are from 2019, which corresponds with the initial selection of the population and sampling of the survey respondents in January 2019. Survey answers are thus collected during the Covid-19 lockdown, whereas consumption data is from the year before the lockdown and thus not influenced by this. Questions in this survey about what SHT the household has is in our assessment not influenced by the lockdown, however, the use of them may be slightly influenced toward more use due to being more at home.

The questionnaire was conducted using online reporting combined with reminders via phone calls. This means that each respondent received a personal link to an online questionnaire via the digital post platform e-Boks, and if they did not respond within a certain period, they were reminded via a phone call to use the link in the digital mailbox. The distributed questionnaire was in Danish, but the initial questions were formulated in English and translated.²

The sampling was done by randomly selecting adults (18 years or older) in Danish households with a smart electricity meter³ and without their own

production of electricity (e.g., solar panels⁴), electric heating,⁵ or registered commercial use. Excluding households with electricity production or being heated by electricity was done to be able to compare the level of consumed electricity only for appliance use between households. Households having EVs were not excluded, but these were very few at this time, as only 2% of all cars in 2019 were electric. Thus, a household with an EV is a possible (minor) error in the analysis of electricity consumed for appliance use. Analysis of heating was done based on yearly consumed heating per household as delivered by gas or district heating companies.

The survey sample was selected from a population of 3,495,169 people, where 4,515 people were invited to participate in the survey, and 1,468 people responded to all questions, giving a response rate of 33%. The final number of observations in the regression models was 1,463 due to some missing values.

The sampling meets the international criteria for universal representativity (Eurostat, 2008), and Appendix 1 gives a comparison of the population and survey sample on a list of parameters, which highlights some differences (e.g., the percentage of lower income, younger people, and people living in the capital area are lower in the sample compared to the general population).

Variables

The variables used in the analyses can be divided into three groups. First, questions from the survey included questions about SHT in the respondents' homes. The questions were formulated as follows: "Do you have [insert smart appliance] in your house?", where the question was repeated for each of the following nine smart appliances: voice-controlled units (e.g., Alexa, Google Home, Apple HomeKit), home security systems (e.g., cameras, alarms, locks, smoke detectors), smart lighting, smart plugs, smart thermostats, smart heating control, robotic vacuum cleaner, robotic lawnmower, and smart music systems. The respondents had three answer options: 1.

² The full questionnaire in both Danish and English can be found here: <https://vbn.aau.dk/da/publications/survey-questionnaire-on-households-use-of-smart-home-technology-a> (Trotta et al., 2023).

³ It was expected that all Danish households would have smart meters with remote reading of electricity consumption by the end of 2020 (Danish Energy Agency 2020), so we did not expect a strong bias based on this parameter.

⁴ Only a small percentage of Danish households (fewer than 100,000) are expected to have solar panels (PVs) (Hansen, Jacobsen, et al., 2022a, 2022b).

⁵ Less than 10% of Danish households are expected to have electric heating (www.statistikbanken.dk, register BOL102).

“have and use it”; 2. “have it but do not use it”; 3. “Do not have it”.

Second, data from Danish administrative registers used in the analyses covered socio-demographic characteristics such as income and age, as well as dwelling characteristics such as housing type and size. The variable indicating technical education covered the occupational groups categorized as industrial and technical education, such as working with machines and technology, e.g., engineers and IT-supporters, and craftsmen, e.g., carpenters and electricians. The variable disposable income refers to the amount of money that is left from individual salaries to consumption and savings after taxes and mortgages have been paid. A full list of variables can be found in Appendix 1 with a comparison to the full population. All people living in Denmark are registered by a unique identification number, and this information constitutes administrative records used for purposes like taxation. However, this information is also available for researchers, in anonymized form through secure servers at Statistics Denmark. This means that such data is only accessible in anonymized form (i.e., it is not possible to identify specific individuals or addresses), under a range of restrictions, and only through Statistics Denmark’s servers (Statistics Denmark, 2020).

Third, data on energy consumption were provided by two sources. Electricity consumption data were provided by Statistics Denmark, who collect data on electricity use from the Danish electricity transmission system operator, Energinet. Heating consumption data (gas and district heating) were provided by the Danish Property Assessment Agency and uploaded to Statistic Denmark’s registers in anonymized form. Data on heating consumption were only available for respondents living in single-family houses and heated by either gas or district heating which restricted the models using this data to 749 observations.

Methods

The first part of the analysis descriptively investigates the diffusion of smart home technology. Specifically, we illustrated the proportion of respondents who stated that they have any of the nine smart appliances in their house. In addition, SHTs are classified according to the type of service they provide. This includes:

- 1) Entertainment
- 2) Home security
- 3) Robotic help
- 4) Electricity management
- 5) Heating management.

In the second part of the analysis, the factors influencing the probability of Danish households adopting smart home technologies are examined within a standard discrete choice probit model framework. The probability of smart home technology adoption by households is described as follows:

$$Pr(y_i = 1) = \Phi(\beta'x_i) \quad (1)$$

where Φ represents the cumulative normal distribution, x_i is a vector of explanatory variables with socio-demographic and dwelling characteristics of household i and β' is the parameter vector to be estimated. The probit model assumes that while the variable y_i takes the values of 0 (no SHT adoption) and 1 (at least one SHT adopted and in use), there is a latent, unobserved continuous variable that establishes a linear relationship between the variables of interest and determines the value of y_i .

Due to the nonlinear nature of the probit models, we used the average marginal effects (AMEs) to estimate the effect of each explanatory variable (socio-demographic, dwelling, and households) on SHT adoption according to the type of service they provide (e.g., entertainment, home security, etc.). The Hosmer and Lemeshow goodness-of-fit tests (all P values > 0.05), the McFadden Pseudo R², and the percentage correctly predicted by the probit models are given.

Finally, to investigate the correlation between adoption of SHT and electricity consumption, we estimated an ordinary least squares (OLS) model. The electricity demand function is then specified as follows:

$$\ln E_i = \alpha_0 + SHT_i + a_{SD}SD_i + a_{DH}DH_i + \varepsilon_i \quad (2)$$

where E_{it} is the actual annual electricity consumption (kWh) from January 1 to December 31, 2019, SHT_i denotes the five SHT services, SD_i is a vector of respondent socio-demographic characteristics such as income, age, education, and gender, DH_i is a vector of dwelling and household characteristics such as dwelling type, dwelling tenure, household type, and

Table 1 Overview and summary statistics for dependent variables

Variable	Description	Outcomes	Regression model
SHT	Has at least 1 SHT in the household, yes (= 1) or no (= 0)	N = 1,468 Mean = 0.553 Std. Dev. = 0.497	Probit
Heating management	Smart thermostats or smart heating control, yes (= 1) or no (= 0)	N = 1,468 Mean = 0.126 Std. Dev. = 0.332	Probit
Electricity management	Smart plugs or smart lighting, yes (= 1) or no (= 0)	N = 1,468 Mean = 0.140 Std. Dev. = 0.347	Probit
Entertainment	Voice-control or music system, yes (= 1) or no (= 0)	N = 1,468 Mean = 0.295 Std. Dev. = 0.456	Probit
Home security	Home security system, yes (= 1) or no (= 0)	N = 1,468 Mean = 0.240 Std. Dev. = 0.427	Probit
Robotic help	Robotic vacuum cleaner or robotic lawn mower, yes (= 1) or no (= 0)	N = 1,468 Mean = 0.173 Std. Dev. = 0.378	Probit
Electricity consumption	Amount of kWh of electricity used in 2019	N = 1,463 Mean = 3,003.5 Std. Dev. = 1,895.6	Ordinary least square (OLS) regression
Heating consumption	Amount of kWh of energy used for space heating and domestic hot water in 2019, gas or district heating	N = 749 Mean = 22,074.1 Std. Dev. = 16,987.8	Ordinary least square (OLS) regression

number of rooms, and ε_{it} is the error term. The variables annual electricity consumption and annual heating consumption were logarithmically transformed to ensure a normal distribution. Table 1 summarizes the dependent variables used in the analyses.

Results

The analysis consists of three steps: first, we describe the diffusion of different forms of SHT; second, we identify differences in the adoption of SHT across social groups; third, we model the association between SHT uptake and energy consumption for appliances and heating.

Diffusion of SHT

Table 2 presents the diffusion of SHT based on the representative survey among Danish households. In the questionnaire, we presented a list of SHTs and asked respondents whether they had or used these in their homes. In total, 55.3% (812) of the respondents

stated that they had at least one of the appliances, and the results showed that home security systems (e.g., cameras, alarms, locks, and smoke detectors) were the most prevalent with 22.2% stating that they had and used such systems. An additional 2% stated that they had but did not use them. This was followed by smart music systems with 19% and smart lighting with 1.7% of respondents. Smart plugs (5.4%) were the least common SHT according to this survey. Table 2 shows that voice-control devices (e.g., Alexa, Google Home, and Apple HomeKit) had the highest percentage (8.5%) of respondents stating that they had them but did not use them.

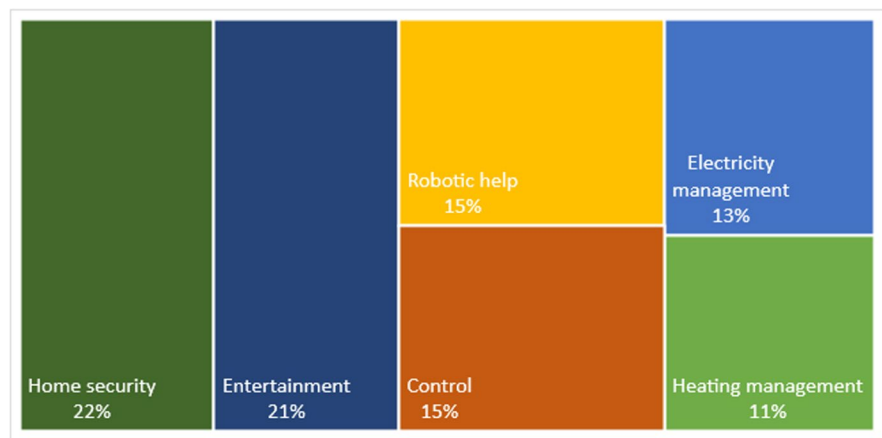
As several of the SHTs relate to similar services, we grouped the SHTs into five services that they are expected to provide.

Figure 1 shows the percentage of the six SHT services in the sample of Danish households. The most popular SHT service is home security with 22%, followed by entertainment (music systems) with 21%. Then follows robotic help (robotic lawnmowers and vacuum cleaners) and control (voice-control devices), both represented by 15%. The least common were the

Table 2 Responses to questions about the availability and use of smart home devices in the household. Number of observations in brackets. Sorted by the category 'Have and use it'. Sample of 1,468 observations

	Have and use it	Have it but do not use it	Do not have it
Home security system	22.2% (419)	2.0% (37)	75.9% (1,435)
Smart music system	19.0% (359)	1.8% (33)	79.2% (1,495)
Smart lighting	1.7% (202)	1.0% (19)	88.3% (1,669)
Robotic lawnmower	8.4% (158)	0.4% (7)	91.3% (1,722)
Smart thermostats	8.0% (151)	0.9% (17)	91.1% (1,720)
Smart heating control	7.8% (148)	1.0% (19)	91.2% (1,721)
Robotic vacuum cleaner	7.7% (146)	2.2% (42)	9.0% (1,699)
Voice-control devices	6.9% (131)	8.5% (161)	84.6% (1,603)
Smart plugs	5.4% (101)	1.0% (19)	93.7% (1,769)

Fig. 1 Percentage of Danish households demanding a specific smart home technology service from a sample of 1,468 observations. Note that the figures sum to more than 100%, as households may have more than one type of SHT



two services relating to household energy management in the form of electricity consumption control (smart lighting and smart plugs) and heating consumption control (smart heating control and smart thermostats).

Differences in SHT uptake

In addition to the general uptake of SHT among the surveyed Danish households, we investigated which households tend to have and use SHT. We used probit regression models to empirically investigate the magnitude of the effects of socio-demographic, dwelling, and household characteristics on the probability of SHT adoption, and Table 3 shows the average marginal effects (AMEs) of probit regression models for each of the SHT services.

Generally, there are few significant associations between the socio-economic and demographic characteristics and having SHT (Any SHT). However, the

respondents above 60 years old seem less likely to adopt SHT compared to the younger age groups. This is particularly true for electricity management and entertainment services, where the group of 71 years or older seems more likely to have smart heating appliances, while for robotic help, it is the group aged 18 to 40 who appear more likely to demand such services.

Furthermore, those living in an apartment seem less likely to have and use SHT, particularly in terms of home security and robotic help. This probably illustrates how these services are primarily designed for detached housing, for example, houses with a garden.

There are some significant associations for specific SHT services. The highest income group (€50,000 or more), based on the individual respondents' disposable income, is more likely to have smart security systems, while highly educated individuals are more likely to have robotic help, those with a technical

Table 3 Coefficients of probit models for each SHT service. Clustered standard errors at the individual level are in parentheses

	Any SHT	Heating man- agement	Electricity management	Entertain- ment	Control	Home security	Robotic help
<i>Disposable indi- vidual income (Ref. = Less than €20,000)</i>							
€20,000 to €30,000	-0.050 (0.12)	-0.294 (0.16)	-0.026 (0.17)	-0.190 (0.15)	0.250 (0.21)	0.212 (0.15)	-0.162 (0.17)
€30,000 to €40,000	0.114 (0.13)	-0.059 (0.16)	0.024 (0.18)	-0.102 (0.15)	0.240 (0.22)	0.259 (0.15)	0.174 (0.17)
€40,000 to €50,000	0.097 (0.14)	0.013 (0.18)	-0.016 (0.19)	0.059 (0.16)	0.227 (0.24)	0.305 (0.17)	0.139 (0.18)
€50,000 or more	0.286 (0.15)	-0.070 (0.19)	0.235 (0.20)	0.236 (0.17)	0.448 (0.24)	0.650*** (0.17)	0.076 (0.19)
<i>Educational level (Ref. = Shorter or not regis- tered)</i>							
Vocational	0.056 (0.10)	-0.020 (0.13)	-0.137 (0.12)	0.117 (0.12)	0.123 (0.15)	-0.038 (0.11)	0.378** (0.13)
University, col- lege, or longer	0.044 (0.09)	-0.007 (0.13)	-0.196 (0.12)	0.168 (0.12)	-0.010 (0.16)	-0.236* (0.11)	0.396** (0.13)
<i>Technical educa- tion (Ref. = No)</i>							
Yes	0.176 (0.10)	0.334** (0.12)	0.213 (0.12)	0.106 (0.11)	0.134 (0.14)	0.096 (0.10)	-0.117 (0.12)
<i>Gender (Ref. = Female)</i>							
Male	-0.007 (0.08)	0.047 (0.10)	0.192* (0.10)	0.156 (0.09)	0.084 (0.12)	-0.124** (0.08)	-0.015 (0.10)
<i>Partner (Ref. = No partner)</i>							
Lives with partner	0.154 (0.08)	0.219* (0.11)	0.087 (0.11)	0.274** (0.10)	0.255 (0.13)	0.202* (0.09)	0.179 (0.11)
<i>Child (Ref. = No child)</i>							
Child in house- hold	0.173 (0.10)	0.104 (0.13)	-0.072 (0.13)	0.183 (0.11)	0.177 (0.15)	0.043 (0.12)	0.192 (0.13)
<i>Age (Ref. = 18 to 40 years)</i>							
40s	-0.230 (0.12)	0.338* (0.17)	-0.112 (0.14)	-0.302* (0.13)	-0.268 (0.16)	0.253 (0.14)	-0.448** (0.14)
50s	-0.252* (0.12)	0.177 (0.17)	-0.254 (0.14)	-0.411** (0.13)	-0.260 (0.17)	0.018 (0.14)	-0.498** (0.15)
60s	-0.400** (0.13)	0.419* (0.17)	-0.492** (0.16)	-0.609*** (0.14)	-0.528* (0.21)	0.116 (0.15)	-0.572*** (0.16)
71 or older	-0.350** (0.13)	0.564** (0.17)	-0.780*** (0.18)	-0.780*** (0.15)	-0.584** (0.20)	0.297 (0.15)	-0.389* (0.17)
<i>Dwelling owner- ship (Ref. = Rented)</i>							
Owner-occupied	0.187 (0.11)	-0.095 (0.16)	0.067 (0.15)	-0.042 (0.13)	-0.205 (0.16)	-0.064 (0.13)	0.099 (0.16)

Table 3 (continued)

	Any SHT	Heating management	Electricity management	Entertainment	Control	Home security	Robotic help
<i>Dwelling type</i> (Ref. = Detached)							
Terraced	-0.068 (0.12)	-0.234 (0.16)	-0.056 (0.15)	-0.007 (0.13)	0.078 (0.17)	-0.269* (0.13)	-0.418** (0.16)
Apartment	-0.321** (0.12)	-0.391* (0.16)	-0.194 (0.16)	-0.106 (0.15)	-0.337 (0.19)	-0.570*** (0.15)	-0.722*** (0.18)
<i>Number of rooms</i> (Ref. = Max. 3 rooms)							
4 rooms	-0.107 (0.10)	-0.002 (0.13)	-0.065 (0.13)	0.042 (0.12)	-0.161 (0.15)	-0.071 (0.11)	0.006 (0.13)
5 rooms or more	-0.080 (0.11)	-0.118 (0.14)	-0.002 (0.14)	0.131 (0.12)	-0.222 (0.16)	-0.030 (0.12)	0.073 (0.14)
Pseudo R2	0.053	0.053	0.056	0.090	0.060	0.058	0.113
Number of observations	1,468	1,468	1,468	1,468	1,468	1,468	1,468

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4 Ordinary least square (OLS) regression estimates with a log-linear model including control variables

	Electricity consumption (log of kWh)	Heating consumption (log of kWh)
	Coef. (SE)	Coef. (SE)
<i>Smart home technology service</i>		
Heating management	0.003 (0.04)	-0.064 (0.06)
Electricity management	0.070* (0.04)	0.141** (0.07)
Robotic help	-0.014 (0.03)	-0.050 (0.05)
Home security	0.088*** (0.03)	-0.003 (0.05)
Entertainment	-0.007 (0.03)	0.028 (0.06)
Control	0.067 (0.05)	-0.004 (0.09)
R2	0.512	0.212
Number of observations	1,463	749

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Standard errors in parentheses. The full table is shown in Appendix 2

education are more likely to have smart heating management, and those with a partner are more likely to have SHT for entertainment.

The analysis indicates that gender, children, dwelling ownership, and number of rooms are not associated with having and using SHT and that education and income are only associated to a limited extent. An additional analysis (not reported) only on single households did also not show any significant association with gender. This indicates that gender seems less important for the uptake of SHT, which is quite surprising considering the qualitative studies on this topic (Aagaard & Madsen, 2022). However, it is

important to note that the variable gender refers here to the survey respondent and therefore does not give any information about who bought and uses the SHT.

SHT and energy used for appliances and heating

The final part of the analysis investigates the correlation between SHT services and energy consumption, divided into electricity for appliance use and gas or district heating for heating purposes. Table 4 shows the results of two OLS regression models, where the first estimates correlations with electricity consumption for appliances and the

second estimates correlations with heating consumption for a subsample of households living in single-family houses. Both electricity for appliances and heating consumption are measured as the log of kWh.

The results of the OLS regression model on electricity consumption in Table 4 show that the home security service is significantly higher with a 99% significance level. This indicates that households with home security tend to consume 8.8% more electricity than other households when controlling for other SHT services and household characteristics. Alarm systems typically have a power use in the range of 1–20 Watts, which accounts for a yearly consumption of 10–200 kWh, which is considerably lower than 8.8% of an average household's electricity consumption of approximately 4,000 kWh. Thus, our analysis does not suggest that the alarm alone is responsible for the 8.8% higher consumption, but that it can be an indicator of a home with many electric appliances, and high use of appliances. In addition, the estimate for electricity management is significantly positive, but only at a 90% level. This indicates that households with electricity management tend to consume 7.8% more but with a lower level of confidence.

For heating consumption, the estimate for electricity management is significant at a 95% significance level. This suggests that households with SHT for electricity management, e.g., smart lighting, tend to consume 14.1% more heating. In this case, electricity management could be an indicator of presence in the home or homely practices, and thereby demand energy for heating. Finally, there is no significant correlation between having heating management and heating consumption, indicating that SHT service of heating management is not linked to higher or lower heating demand.

The OLS regression models control for a range of socio-demographic and dwelling characteristics, and the model with heating consumption also controls for the size of the house (full table in Appendix 2). It is also worth noting that it was only possible to conduct the heating consumption analysis for the respondents living in single-family detached dwellings, supplied with gas or district heating.

Discussion and conclusions

Smart home technology (SHT) is increasingly entering homes to provide services such as energy management, security, comfort, and convenience in everyday life. For example as part of HEMS with purposes of energy saving and demand control (Mahapatra & Nayyar, 2022). However, there is still little evidence of the actual uptake of SHT, its determinants, or its influence on energy consumption.

According to Eurostat data, Denmark is among the frontrunners in adopting SHT for security and household appliances. Using Denmark as a case study and based on a representative survey questionnaire among 1,468 Danish households combined with register data from 2019, this study investigated (i) the diffusion of various types of SHT in Denmark, (ii) the social differences in the uptake of SHT, and (iii) the correlation between SHT and energy consumption.

First, it shows that home security and entertainment were the most common SHT services, followed by robotic help.

Second, the analysis also showed that older age groups were less likely to adopt SHT, especially for entertainment and electricity management. The group under 40 years old was more likely to have and use household robotic help (lawnmowers and vacuum cleaners) than other age groups. However, as an exception, it appears that the group aged 71 or older was more likely to have and use heating management as an SHT service. The overall picture is in line with previous studies that also indicate a stronger interest in SHT among younger age groups (Arthanat et al., 2019, 2020; Pal et al., 2018; Parag & Butbul, 2018).

In terms of income and education, there are only a small number of significant correlations. First, the highest income group was more likely to have smart home security. Second, individuals with a technical education tended to have smart heating management. Third, a longer education seemed to be associated with having robotic help in the household, and fourth, living with a partner was associated with a tendency to have and use SHT for entertainment. There are some examples in previous research that link SHT adoption to a higher income (Sanguinetti et al., 2018a, 2018b; Shin et al., 2018) and not living alone

(Arthanat et al., 2019), and this study partly underlines this.

Third, from a policy perspective, smart heating control has been promoted as a way to save energy, but how realistic this has also been questioned, and it could be that the opposite is true (Darby, 2018; Hargreaves et al., 2017b; Peffer et al., 2011; Strengers & Nicholls, 2017). The unique data opportunities in Denmark allow us to combine survey data with energy consumption data, separated for respectively energy for heating (gas or district heating) and electricity for appliance use. To our knowledge, this has been the first opportunity to combine such representative quantitative data. This paper is therefore very important in shedding light on the correlations between SHT and energy consumption. The results indicate that there is no correlation between the actual level of energy consumed for heating and having smart heating control. Policy assumptions about any potential energy reduction following smart heating control should therefore take this into account. From this, it seems that having smart heating control is not associated with neither saving nor consuming more energy for heating. This could be the result of two opposing tendencies. First, it is well-known that different types of efficient heating technologies imply changing norms of comfort and that even higher levels of comfort are prioritized over any possible savings, as with performance gaps (Hansen & Gram-Hanssen, 2023), and smart heating control could likely have similar implications. Future studies that include temperature levels in homes with smart heating could be relevant. Second, is the opposite case where the savings result from making it easier to control heat and only use it when needed (Hansen et al., 2022a, 2022b). This paper did not include electric heating, though in a future with expectations of more electric heating, the time of use of electricity, and reducing peak consumption and shifting towards times with high renewable production will be increasingly relevant from a grid perspective (Smale et al., 2017; Torriti, 2015). In this case, smart control of heating will likely be beneficial.

Concerning electricity for appliance use, we investigated the association between SHT adoption and energy consumption, in the form of heating and electricity. We found a modest association between smart electricity management, such as smart lighting and

smart plugs, and higher electricity consumption. However, surprisingly smart electricity management was associated with higher heating consumption, which was not the case for smart heating management, such as smart thermostats. This indicates that SHT services of heating management are not linked to higher or lower heating demand, whereas SHT services of electricity management are linked to higher heating demand, and with less confidence, also to higher electricity consumption. Finally, we found a correlation indicating that having home security systems is associated with higher electricity consumption. The home security systems analysis indicated an 8.8% higher electricity consumption, which is higher than what is reasonable to believe can be ascribed alone to the electricity demanded by the security system itself.

Although this analysis took other household and dwelling characteristics into account, the associations with electricity consumption might reflect other household practices that are indirectly linked to SHT, for example, more energy-intensive lifestyles in general. However, from a policy perspective, it is important to emphasize that this study cannot confirm that smart energy management will contribute to lowering energy consumption, neither related to heating nor to electricity for appliances. Our analysis indicates that SHT for energy management can be associated with higher heating consumption, but this requires further investigation.

Despite the richness of the dataset used in the paper, one limitation of this study is that it does not cover all forms of appliances and services linked to SHT, for example, smart TVs and smart fridges, nor does it capture varying degrees of smartness of the selected smart appliances. Also, ownership of electric vehicles which is not accounted for in the analysis may have influenced the result, although the uptake of EVs at the time of the data collection was low. Furthermore, our data may quickly appear outdated as the market for SHT is expanding rapidly. Future research could address these limitations with updated forms of SHT services. Finally, future studies should include the use of SHT in a future electrified society where flexibility and time of use become increasingly important.

Appendix 1

	Population		Sample	
	Mean = 2,831.8	Std. Dev. = 14,543.1	Mean = 2,993.3	Std. Dev. = 1,90.4
Electricity consumption (in 2019)	%	N	%	N

Disposable income

Less than €20,000	22.7%	771,147	11.4%	168
€20,000 to €30,000	27.4%	929,290	25.4%	373
€30,000 to €40,000	22.6%	766,683	27.3%	400
€40,000 to €50,000	13.5%	456,422	18.2%	267
€50,000 or more	13.9%	470,851	17.7%	260

Educational level

Shorter or not registered	36.2%	1,228,290	24.2%	355
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Vocational	32.3%	1,096,037	36.0%	528
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University, college, or longer	31.5%	1,070,066	4.0%	585
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Technical education (yes = 1)	17.5%	594,016	2.0%	294
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Male (yes = 1)	48.3%	1,637,815	45.4%	666
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Lives with partner (yes = 1)	59.3%	2,011,505	61.2%	898
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Child (yes = 1)	32.0%	1,086,251	26.7%	392
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Age

18 to 40 years	31.4%	1,066,770	15.3%	225
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40s	17.7%	601,442	18.7%	275
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50s	18.1%	613,111	23.4%	343
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60s	14.8%	503,133	2.9%	307
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71 or older	18.0%	609,937	21.7%	318
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Owner-occupied (yes = 1)	55.1%	1,871,534	66.8%	980
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Dwelling type

Detached	48.1%	1,631,454	58.2%	854
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Terraced	14.7%	497,631	14.7%	215
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Apartment	37.3%	1,265,308	27.2%	399
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Number of rooms

Max. 3 rooms	4.0%	1,356,364	34.2%	502
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4 rooms	26.7%	906,681	28.9%	424
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5 rooms or more	33.3%	1,131,348	36.9%	542
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Area

Capital area	24.8%	842,022	14.7%	215
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50,000 or more	19.2%	650,931	17.8%	261
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10,000 to 50,000	21.6%	733,308	23.8%	350
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2,000 to 10,000	17.1%	581,428	23.4%	344
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Less than 2,000	17.3%	586,704	2.3%	298
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	Population		Sample	
	Mean = 2,831.8	Std. Dev. = 14,543.1	Mean = 2,993.3	Std. Dev. = 1,90.4
Electricity consumption (in 2019)	%	N	%	N
Number of observations	3,394,393		1,468	

Appendix 2

	Electricity consumption (log of kWh) Coef. (SE)	Heating consumption (log of kWh) Coef. (SE)
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Smart home technology service

Heating management	0.003 (0.04)	-0.064 (0.06)
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Electricity management	0.070* (0.04)	0.141* (0.06)
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Robotic help	-0.014 (0.03)	-0.050 (0.05)
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Home security	0.088*** (0.03)	-0.003 (0.05)
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Entertainment	-0.007 (0.03)	0.028 (0.06)
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Control	0.067 (0.05)	-0.004 (0.09)
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Disposable income (Ref. = Less than €20,000)

€20,000 to €30,000	-0.006 (0.04)	0.004 (0.09)
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€30,000 to €40,000	-0.006 (0.04)	-0.033 (0.09)
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€40,000 to €50,000	-0.027 (0.05)	-0.049 (0.10)
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€50,000 or more	0.037 (0.05)	0.025 (0.10)
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Educational level (Ref. = High school, shorter or not registered)

Vocational	-0.016 (0.03)	-0.023 (0.07)
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University, college, or longer	-0.052 (0.03)	0.084 (0.07)
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Technical education (Ref. = No)

Yes	-0.014 (0.03)	-0.073 (0.06)
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Gender (Ref. = Female)

Male	-0.022 (0.03)	0.049 (0.05)
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Partner (Ref. = No partner)

Lives with partner	0.345*** (0.03)	0.084 (0.06)
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Child (Ref. = No child)

Child in household	0.243*** (0.04)	0.072 (0.07)
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	Electricity consumption (log of kWh) Coef. (SE)	Heating consumption (log of kWh) Coef. (SE)
<i>Age (Ref. = 18 to 40 years)</i>		
40 s	0.059 (0.04)	-0.075 (0.08)
50 s	0.148*** (0.04)	-0.006 (0.09)
60 s	0.109** (0.04)	-0.020 (0.10)
71 or older	0.043 (0.04)	0.068 (0.11)
<i>Dwelling ownership (Ref. = Rented)</i>		
Owner-occupied	0.141*** (0.04)	0.186* (0.10)
<i>Dwelling type (Ref. = Detached)</i>		
Terraced	-0.130*** (0.04)	
Apartment	-0.346*** (0.05)	
<i>Number of rooms (Ref. = Max. 3 rooms)</i>		
4 rooms	0.054 (0.03)	0.021 (0.08)
5 rooms or more	0.166*** (0.04)	0.073 (0.08)
<i>Town size (Ref. = Capital area)</i>		
50,000 or more	0.008 (0.04)	-1.099*** (0.12)
10,000 to 50,000	0.053 (0.04)	-0.833*** (0.12)
2,000 to 10,000	0.055 (0.05)	-1.007*** (0.11)
Less than 2,000	0.226*** (0.05)	-0.857*** (0.12)
<i>Heated area (m²)</i>		
Constant	7.359*** (0.08)	9.867*** (0.20)
R ²	0.512	0.212
Number of observations	1,463	749

Ordinary least square (OLS) regression estimates with log-linear model including control variables. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Standard errors in parentheses

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Data availability The Danish register data used in the analysis is not publicly available. However, the survey data used is available from this weblink: <https://vbn.aau.dk/da/publications/survey-questionnaire-on-households-use-of-smart-home-technology-a>. For more information, see Trotta et al. (2023).

Declarations

Conflict of interest The authors have no conflict of interest.

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References

- Aagaard, L. K. (2021). The meaning of convenience in smart home imaginaries: Tech industry insights. *Buildings and Cities*, 2(1), 568–582. <https://doi.org/10.5334/bc.93>
- Aagaard, L. K., & Madsen, L. V. (2022). Technological fascination and reluctance: Gendered practices in the smart home. *Buildings and Cities*, 3(1), 677–691. <https://doi.org/10.5334/bc.205>
- Aagaard, L. K., Christensen, T. H., & Gram-Hanssen, K. (2023). My smart home: An auto-ethnography of learning to live with smart technologies. *Personal and Ubiquitous Computing*, 27(6), 2121–2131. <https://doi.org/10.1007/s00779-023-01725-0>
- Arthanat, S., Wilcox, J., & Macuch, M. (2019). Profiles and Predictors of Smart Home Technology Adoption by Older Adults. *OTJR: Occupation, Participation and Health*, 39(4), 247–256. <https://doi.org/10.1177/1539449218813906>
- Arthanat, S., Chang, H., & Wilcox, J. (2020). Determinants of information communication and smart home automation technology adoption for aging-in-place. *Journal of Enabling Technologies*, 14(2), 73–86. <https://doi.org/10.1108/JET-11-2019-0050>
- Billanes, J., & Enevoldsen, P. (2022). Influential factors to residential building Occupants' acceptance and adoption of smart energy technologies in Denmark. *Energy and Buildings*, 276, 112524. <https://doi.org/10.1016/j.enbuild.2022.112524>
- Chang, S., & Nam, K. (2021). Smart Home Adoption: The Impact of User Characteristics and Differences in Perception of Benefits. *Buildings*, 11, 393. <https://doi.org/10.3390/buildings11090393>
- Darby, S. J. (2018). Smart technology in the home: Time for more clarity. *Building Research & Information*, 46(1), 140–147. <https://doi.org/10.1080/09613218.2017.1301707>
- Ford, R., Pritoni, M., Sanguinetti, A., & Karlin, B. (2017). Categories and functionality of smart home technology for energy management. *Building and Environment*, 123, 543–554. <https://doi.org/10.1016/j.buildenv.2017.07.020>
- Furszyfer Del Rio, D. D. (2022). Smart but unfriendly: Connected home products as enablers of conflict. *Technology*

- in *Society*, 68, 101808. <https://doi.org/10.1016/j.techsoc.2021.101808>
- Furszyfer Del Rio, D. D., Sovacool, B. K., & Martiskainen, M. (2021). Controllable, frightening, or fun? Exploring the gendered dynamics of smart home technology preferences in the United Kingdom. *Energy Research & Social Science*, 77, 102105. <https://doi.org/10.1016/j.erss.2021.102105>
- Gram-Hanssen, K., & Darby, S. J. (2018). “Home is where the smart is”? Evaluating smart home research and approaches against the concept of home. *Energy Research & Social Science*, 37, 94–101. <https://doi.org/10.1016/j.erss.2017.09.037>
- Hansen, A. R., Leiria, D., Johra, H., & Marszal-Pomianowska, A. (2022). Who Produces the Peaks? Household Variation in Peak Energy Demand for Space Heating and Domestic Hot Water. *Energies*, 15(24), 9505. <https://doi.org/10.3390/en15249505>
- Hansen, A. R., Jacobsen, M. H., & Gram-Hanssen, K. (2023). Characterizing the Danish energy prosumer: Who buys solar PV systems and why do they buy them? *Ecological Economics*, 193, 107333. <https://doi.org/10.1016/j.ecolecon.2021.107333>
- Hargreaves, T., & Wilson, C. (2017). *Smart homes and their users*. Springer.
- Hargreaves, T., Wilson, C., & Hauxwell-Baldwin, R. (2018). Learning to live in a smart home. *Building Research & Information*, 46(1), 127–139.
- Janhunen, E., Pulkka, L., Säynäjoki, A., & Junnila, S. (2019). Applicability of the Smart Readiness Indicator for Cold Climate Countries. *Buildings*, 9(4), 102. <https://doi.org/10.3390/buildings9040102>
- Larsen, S. P. A. K., & Gram-Hanssen, K. (2020). When Space Heating Becomes Digitalized: Investigating Competencies for Controlling Smart Home Technology in the Energy-Efficient Home. *Sustainability*, 12(15), 6031. <https://doi.org/10.3390/su12156031>
- Li, W., Yigitcanlar, T., Erol, I., & Liu, A. (2021). Motivations, barriers and risks of smart home adoption: From systematic literature review to conceptual framework. *Energy Research & Social Science*, 80, 102211. <https://doi.org/10.1016/j.erss.2021.102211>
- Lund, H., Østergaard, P. A., Connolly, D., & Mathiesen, B. V. (2017). Smart energy and smart energy systems. *Energy*, 137, 556–565.
- Madsen, L. V., Hansen, A. R., & Larsen, S. P. A. K. (2023). Embodied competencies and smart home technology in energy use: Three ways users integrate smart heating systems in everyday practices. *Energy Efficiency*, 16(6), 55. <https://doi.org/10.1007/s12053-023-10138-0>
- Mahapatra, B., & Nayyar, A. (2022). Home energy management system (HEMS): Concept, architecture, infrastructure, challenges and energy management schemes. *Energy Systems*, 13(3), 643–669. <https://doi.org/10.1007/s12667-019-00364-w>
- Marikyan, D., Papagiannidis, S., & Alamanos, E. (2019). A systematic review of the smart home literature: A user perspective. *Technological Forecasting and Social Change*, 138, 139–154. <https://doi.org/10.1016/j.techfore.2018.08.015>
- Pal, D., Funilkul, S., Vanijja, V., & Papisratorn, B. (2018). Analyzing the Elderly Users’ Adoption of Smart-Home Services. *IEEE Access*, 6, 51238–51252. <https://doi.org/10.1109/ACCESS.2018.2869599>. Presented at the IEEE Access.
- Pantzar, M. (1997). Domestication of Everyday Life Technology: Dynamic Views on the Social Histories of Artifacts. *Design Issues*, 13(3), 52. <https://doi.org/10.2307/1511941>
- Parag, Y., & Butbul, G. (2018). Flexiwatts and seamless technology: Public perceptions of demand flexibility through smart home technology. *Energy Research & Social Science*, 39, 177–191. <https://doi.org/10.1016/j.erss.2017.10.012>
- Peffer, T., Pritoni, M., Meier, A., Aragon, C., & Perry, D. (2011). How people use thermostats in homes: A review. *Building and Environment*, 46(12), 2529–2541. <https://doi.org/10.1016/j.buildenv.2011.06.002>
- Rogers, E. M. (2010). *Diffusion of Innovations* (4th ed.). Simon and Schuster.
- Sanguinetti, A., Karlin, B., & Ford, R. (2018). Understanding the path to smart home adoption: Segmenting and describing consumers across the innovation-decision process. *Energy Research & Social Science*, 46, 274–283. <https://doi.org/10.1016/j.erss.2018.08.002>
- Sanguinetti, A., Karlin, B., Ford, R., Salmon, K., & Dombrowski, K. (2018). What’s energy management got to do with it? Exploring the role of energy management in the smart home adoption process. *Energy Efficiency*, 11(7), 1897–1911. <https://doi.org/10.1007/s12053-018-9689-6>
- Schill, M., Godefroit-Winkel, D., Diallo, M. F., & Barbarossa, C. (2019). Consumers’ intentions to purchase smart home objects: Do environmental issues matter? *Ecological Economics*, 161, 176–185. <https://doi.org/10.1016/j.ecolecon.2019.03.028>
- Shin, J., Park, Y., & Lee, D. (2018). Who will be smart home users? An analysis of adoption and diffusion of smart homes. *Technological Forecasting and Social Change*, 134, 246–253. <https://doi.org/10.1016/j.techfore.2018.06.029>
- Skjølsvold, T. M., Ryghaug, M., & Berker, T. (2015). A traveler’s guide to smart grids and the social sciences. *Energy Research & Social Science*, 9, 1–8. <https://doi.org/10.1016/j.erss.2015.08.017>
- Smale, R., van Vliet, B., & Spaargaren, G. (2017). When social practices meet smart grids: Flexibility, grid management, and domestic consumption in The Netherlands. *Energy Research & Social Science*, 34, 132–140. <https://doi.org/10.1016/j.erss.2017.06.037>
- Sovacool, B. K., & Furszyfer Del Rio, D. D. (2020). Smart home technologies in Europe: A critical review of concepts, benefits, risks and policies. *Renewable and Sustainable Energy Reviews*, 120, 109663. <https://doi.org/10.1016/j.rser.2019.109663>
- Strengers, Y., & Nicholls, L. (2017). Convenience and energy consumption in the smart home of the future: Industry visions from Australia and beyond. *Energy Research & Social Science*, 32, 86–93. <https://doi.org/10.1016/j.erss.2017.02.008>
- Tetteh, N., & Amponsah, O. (2020). Sustainable adoption of smart homes from the Sub-Saharan African perspective. *Sustainable Cities and Society*, 63, 102434. <https://doi.org/10.1016/j.scs.2020.102434>

- Tirado Herrero, S., Nicholls, L., & Strengers, Y. (2018). Smart home technologies in everyday life: Do they address key energy challenges in households? *Current Opinion in Environmental Sustainability*, 31, 65–70. <https://doi.org/10.1016/j.cosust.2017.12.001>
- Torriti, J. (2015). Peak Energy Demand and Demand Side Response. *Routledge*. <https://doi.org/10.4324/9781315781099>
- Aagaard, L. K. (2022). When Smart Technologies Enter Household Practices: The Gendered Implications of Digital Housekeeping. *Housing, Theory and Society*, 0(0), 1–18. <https://doi.org/10.1080/14036096.2022.2094460>
- Aldrich, F. K. (2003). Smart Homes: Past, Present and Future. In R. Harper (Ed.), *Inside the Smart Home* (pp. 17–39). London: Springer. https://doi.org/10.1007/1-85233-854-7_2
- Danish Energy Agency. (2020). Liberalisation of the Danish power sector, 1995–2020. An international perspective on lessons learned.
- European Parliament. Directive 2018/844 on Energy Efficiency. , Official Journal of the European Union (2018). <chrome-extension://efaidnbmnnnibpcjpcglclefindmkaj/https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844>. Accessed 22 January 2024
- Eurostat. (2008). *Survey sampling reference guidelines: Introduction to sample design and estimation techniques.* Luxembourg: European Commission.
- Hansen, A. R., & Gram-Hanssen, K. (2023). Over- and under-consumption of residential heating: Analyzing occupant impacts on performance gaps between calculated and actual heating demand. *Journal of Physics: Conference Series*, 2654(1), 012062. <https://doi.org/10.1088/1742-6596/2654/1/012062>
- Hargreaves, T., Wilson, C., & Hauxwell-Baldwin, R. (2017a). Learning to live in a smart home. *Building Research & Information*, 1–13. <https://doi.org/10.1080/09613218.2017.1286882>
- Hargreaves, T., Wilson, C., & Hauxwell-Baldwin, R. (2017). Learning to live in a smart home. *Building Research & Information*, 0(0), 1–13. <https://doi.org/10.1080/09613218.2017.1286882>
- Hohnen, P., & Hansen, A. R. (2022). Forbrug og gæld. In B. Greve, A. Jørgensen, & J. E. Larsen (Eds.), *Det danske samfund: Centrale idéer og principper* (2nd ed., pp. 401–429). København: Hans Reitzels Forlag.
- Statistics Denmark. (2020, September 22). Data confidentiality policy. <https://www.dst.dk/Site/Dst/SingleFiles/GetArchiveFile.aspx?fi=502998790&fo=0&ext=formid>
- Strengers, Y. (2013). *Smart energy technologies in everyday life: smart utopia?* New York: Palgrave Macmillan.
- Trotta, G., Hansen, A. R., Aagaard, L. K., & Gram-Hanssen, K. (2023). *Survey questionnaire on households' use of smart home technology and their time of use of electric appliances*. København: Department of The Built Environment (BUILD), Aalborg University.

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