Social networks and communication behaviour underlying smart home adoption in the UK

Emilie Vrain[a]*, Charlie Wilson[a]

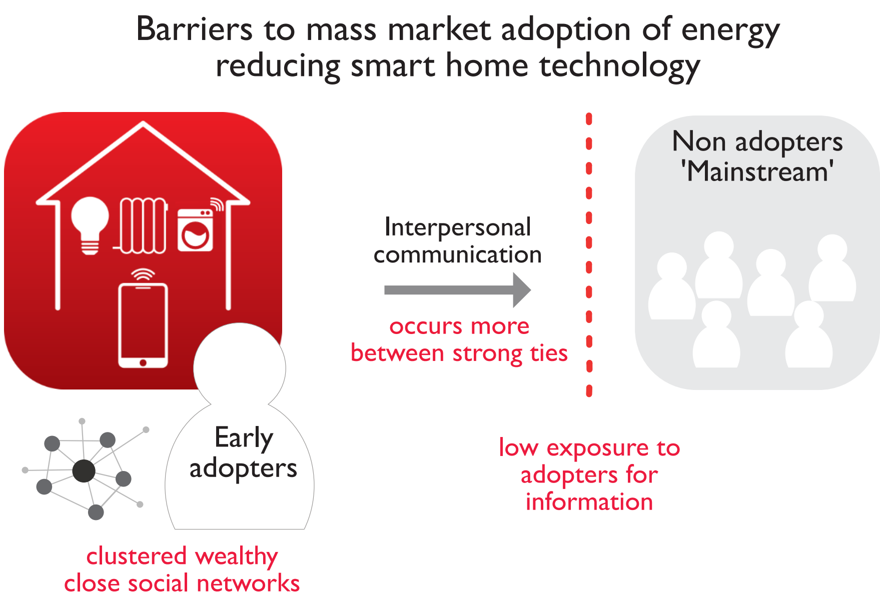
[a]Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, Norfolk NR4 7TJ, UK

* Corresponding author. Email address: e.vrain@uea.ac.uk (E.Vrain)

Abstract

Consumer-facing digital innovations with the potential to reduce carbon emissions often exist in small market niches and their impact has been limited thus far. Using the established Diffusion of innovations theory which considers interpersonal communication amongst social networks to be a vital mechanism for exchanging information, we conducted an online survey in the UK to investigate the social networks and communication behaviours of adopters and non-adopters of three different energy saving smart home technologies. Applying social network analysis and statistically testing hypotheses, our results reveal the potential social barriers to the diffusion of information, with social network structure and characteristics creating obstacles. This research provides necessary insights into real early adopters, confirms the importance of focussing research on the often-neglected social elements of diffusion theory and helps identify marketing strategies and policy actions using social mechanisms to accelerate a low carbon transition.

Graphical abstract



Vrain, E. and Wilson, C. (2021). "Social networks and communication behaviour underlying smart home adoption in the UK." *Environmental Innovation and Societal Transitions* 38: 82-97.

Keywords

Diffusion of Innovations, Social mechanisms, Climate change, Consumer-facing technology, Energy demand

This is a pre-print of a published article. Please cite as:
Vrain, E. and Wilson, C. (2021). "Social networks and communication behaviour underlying smart home adoption in the UK." *Environmental Innovation and Societal Transitions* 38: 82-97.
[doi.org/10.1016/j.eist.2020.11.003]

1. Introduction

Growth in global energy use is largely outpacing decarbonisation, with rates of energy efficiency improvements slowing (IEA, 2019). Energy policy predominantly focusses on energy supply rather than a systemic approach to reducing energy consumption (Creutzig et al., 2018; Eyre and Killip, 2019). To address the urgent challenges associated with climate change and the move towards a low carbon society, changing energy demand has the capacity to support not only reductions in greenhouse gas emissions but also other key energy policy goals such as security and affordability (IPCC, 2018). The residential sector is reported to account for 27% of global energy consumption and 17% of CO_2 emissions (Nejat et al., 2015), with considerable potential for emission reductions through rapid uptake of domestic solutions (Cosar-Jorda et al., 2019; Kesicki, 2012). Established techniques for helping reduce energy use in residential buildings include attic insulation, sealing drafts and double-glazed windows (Watson, 2015). However, with current lifestyle transformations driven by smartphones occurring, harnessing such secular trends through the use of digitally controlled smart home technologies (SHTs), offer the opportunity for modernisation and control, improved efficiency and even greater reductions in energy demand.

In this paper, we refer to SHTs as in-home technological devices equipped with communication network functionality enabling the residents to access, monitor and control (including by remote) the services they provide (Balta-ozkan et al., 2013). These attributes, in addition to automation and adaptive learning (Hargreaves and Wilson, 2017), result in SHTs offering great potential to lower CO_2 emissions through several avenues: i) directly reducing demand e.g. standby consumption (Hittinger and Jaramillo, 2019); ii) enabling effective integrated energy system management i.e. energy being turned on and off, stored, scheduling tasks and shifting peak load (EcoGRID, 2016; IEA, 2019; Young, 2018); iii) increasing efficiency of energy systems with growing shares of intermittently generated energy, predominantly from renewables (OECD, 2019; UKERC, 2019; IEA, 2019); and iv) being a gateway technology for engaging consumers and challenging societal norms of high energy consumption.

Despite the various benefits SHTs offer to the energy system and consumers, the growing number of products on the market (Ford et al., 2017) and industry investments made (Baudier et al., 2018), they remain trapped in small consumer niches (Coskun et al., 2017; Greenough, 2016; McKinsey & Company, 2018). Year-on-year market predictions, expecting rapid expansion, have fallen short (Accenture, 2016; Navigant Research Group, 2012; The Harris Poll, 2015) creating major disappointment within the industry (Accenture, 2016; OECD, 2018). SHTs which offer the greatest potential of improved energy efficiency and carbon reductions - referred to as energy-SHTs from herein - such as smart heating systems (BIT, 2017), smart lighting (Laidi et al., 2019) and smart appliances (Hsu and Lin, 2016) experience some of the slowest rates of adoption. For example, the global market for smart appliances (including fridges, washing machines, tumble dryers, dishwashers and ovens) was projected to grow 650-fold from $40m in 2012 to $26bn in 2019 (IEA, 2013), however revenue amounts to just US$16.9bn in 2019 (Statista, 2019). A survey of 2000 UK residents found just 8% had smart thermostats, 7% had smart lightbulbs and 4% has a smart washing machine (Mintel, 2018). Sales in other SHT market sectors, in particular entertainment and security systems, have seen higher rates of growth (GfK, 2017) but do not provide clear benefits to energy management.

Much of the literature around the adoption of such technologies focusses on aspects of market segment characteristics or attribute appeal amongst consumers. An often-overlooked element is the role of communication within the social system. Therefore, the key research question we aim to address in this paper is: How can the adoption of energy-SHTs be encouraged through social mechanisms?

In order to explore this guiding research question, we first present the theoretical background of innovation diffusion, focusing on social processes and hypothesising expected characteristics of energy-SHT adopters and non-adopters which are considered to positively influence rates of adoption. We then present our methodology of an online survey which targeted both adopters and non-adopters of three energy-SHTs in the UK, followed by the statistical methods used to test the hypotheses. The results and discussion provide insights into the elements which are not consistent with the literature and could potentially be hindering the diffusion process.

2. Theoretical foundation and hypotheses

2.1 Diffusion of innovations through social mechanisms

Whilst the diffusion process of new products and services has become increasingly complex and multifaceted (Linton, 2002), the most challenging part of an innovation's diffusion process is known as 'the chasm' (Moore, 2014). The point at which an innovation goes from being adopted by the minority – roughly made up of 16% of the population known as the *innovators* and *early adopters* - to the mainstream majority. The SHT market is commonly reported to be struggling to overcome the chasm (e.g. Greenough, 2016), with market shares data reinforcing such assertions. Strategies to accelerate diffusion beyond the chasm often draw upon marketing, economic and psychology literature, discovering barriers and solutions by assessing an innovation's attributes, the market dynamics and consumer preferences. The Diffusion of Innovations (DoI) (Rogers, 2003) is a well-established theory which brings together these elements, providing a robust framework.

A critical element of Rogers' (2003) DoI theory is the importance of social processes and the influence of social networks through communication channels. However, research on the diffusion of SHTs tends to focus predominantly on other elements of DoI or derivatives of the framework such as the technology acceptance model (TAM) which centres around the intention to adopt according to perceived innovation characteristics (namely usefulness). Examples include research on: i) the adoption-decision process (e.g. Ford et al., 2016; Sanguinetti et al., 2018); ii) consumer intention to adopt (using variants of TAM) (Hubert et al., 2019; Park et al., 2018a; Shin et al., 2018; Whittle et al., 2020; Yang et al., 2018); iii) a specific group of users such as older adults (Demiris et al., 2004) or technology enthusiasts (Mennicken and Huang, 2012); and iv) a variety of combinations of the above i.e. a specific group of potential users' intention to adopt (Baudier et al., 2018) or consumer intentions to adopt based on environmental concerns, beliefs and perceived usefulness (Schill et al., 2019). Many scholars (Gram-Hanssen and Darby, 2018; Hong et al., 2019; Shin et al., 2018; Wilson et al., 2015) highlight that there is a lack of research which studies actual adopters of SHTs, and that gathering insights from early adopters is essential for facilitating the widespread uptake of SHTs since they are regarded as the main driver of the consumer market (Moore, 2014).

Darby (2019) stresses how little attention has focussed on person-to-person interactions regarding SHT that could aid an understanding of their adoption. The limited research which has involved early adopters has often involved small sample sizes for qualitative data collection (e.g. Coskun et al., 2017; Mennicken and Huang, 2012). Some empirical work on the role of social networks in the diffusion of energy innovations exists (Bale et al., 2013; Fell et al., 2009; Mcmichael and Shipworth, 2013) but no research has investigated their role in energy-SHT adoption nor the communication behaviours of adopters.

Copious examples of both empirical and theoretical research support the concept that social networks and social influence processes through communication channels can be harnessed to help innovation diffusion (Mcmichael and Shipworth, 2013; Sriwannawit and Sandström, 2014). Early adopters are considered to be role models and opinion leaders who play a central part within social systems for the adoption of innovations, typically respected by their peers and asked for advice and information. They help non-adopters overcome concerns, hesitations and resistance, reducing uncertainties and perceived risks regarding an innovation and thus leading to greater adoption amongst their social networks (Rogers, 2003, p. 291). It is this premise which guides our study to investigate the social network characteristics and communication behaviours of energy-SHT early adopters and non-adopters. Testing hypotheses informed by the literature on the expected characteristics and behaviours for successful innovation diffusion provide insights into which traits do not conform to expectations and therefore highlighting potential reasons as to why energy-SHTs are stuck in the early adopter niche. Using DoI as a systematic framework, this research makes several important contributions to the literature: i) collecting insights from actual adopters of SHTs; ii) empirically testing the applicability of

DoI for energy-SHTs; iii) identifying which social elements of the diffusion process are potentially hindering adoption and iv) helping to inform strategies and identify solutions to overcome market stagnation.

2.2 Social network characteristics

Concepts surrounding DoI and social network theory argue that individuals' decision making does not occur in a social vacuum, nor thoughtlessly conform to broad social norms (Granovetter, 1973). The social network in which an individual is embedded is said to influence their attitudes, behaviour and adoption decisions (Berg, 2009; Burt et al., 2013; Gladwell, 2009). The number of relationships (also referred to as ties) an individual maintains is one important variable for diffusing information of an innovation. Rogers (2003, p. 290) states that early adopters are expected to have large social networks with whom they share information about an innovation. Granovetter (1973) suggests a higher number of connections and interactions with people considered as acquaintances (weak ties) increases the likelihood of new information, resources and support coming from a wider variety of contexts. This is particularly relevant for new innovations (Valente, 1995).

In addition to the number of ties, another network characteristic considered to have an impact on diffusion is homophily, the tendency for individuals to associate and bond with similar others, sharing common characteristics such as beliefs, values, interests and education (Valente, 2010). Psychology studies reveal we are more likely to communicate information amongst homophilous groups of people rather than diverse - heterophilous - groups (Rogers, 2003, p. 341). Therefore, one of the most pervasive effects of homophily is that it can cause social networks to become highly clustered. Strong homophily-driven clustering can hinder communication, learning and information diffusion across a social system, leading to knowledge and behaviours becoming trapped in social spaces (Muller and Peres, 2019). For efforts to reduce energy demand or improve environmental sustainability, clustering of knowledge and behaviour, trapping sustainable behaviours in niches, is of particular concern (Barnes et al., 2016). In order to aid innovation diffusion, the optimal social network characteristics for an early adopter are to be: 1) socially accessible through a high number of weak ties; 2) heterophilious and 3) non-clustered (Choi et al., 2010; Parry et al., 2012; Peres, 2014; Rogers, 2003, p. 362). Such social network characteristics fundamentally impact the dynamical (i.e. communication) processes within it (Borgatti et al., 2014), thus, highlighting the importance of collecting contextual data alongside more specific data on adopters' communication channels and behaviour.

2.3 Communication channels – information sources

The adoption decision process for an innovation can be informed by a variety of different communication channels, each playing a particular influential role (Rogers, 2003, p. 204). Mass media communication channels are generally rapid and more effective at informing an audience of potential adopters about the existence of an innovation, leading to awareness-knowledge. Specialist media is considered to provide the detailed know-how information (Valente, 2010), whereas, communication amongst social networks, otherwise known as interpersonal channels, are more likely to impact upon decisions through persuasion (Palm, 2017; Rogers, 2003, p. 205).

During the early stages of an innovation's diffusion, a small percentage of the population will be adopters or even be aware of it at all. Hence, innovators and early adopters must rely upon mass media and specialist media to become informed as little interpersonal knowledge exists (Rogers, 2003, p. 211). Darby (2019)'s investigation on customers of smart technology retrofits reported an extensive list of different specialist sources of communication needed. To help innovations spread from market niches to the mainstream, early adopters play a vital role of sharing trusted knowledge and information to non-adopters within their social networks. Such interpersonal communication channels (verbal or electronic conversations) provide reassurance and reduce perceived uncertainties from first-hand experience of an innovation (Szmigin and Piacentini, 2015).

With energy-SHTs situated inside homes, in the private domain and often out of sight, social influences such as neighbourhood effects are less significant, rendering interpersonal communication to be vital for diffusion (Wolske et al., 2020). Studies which have demonstrated the importance of interpersonal communication channels through social networks for encouraging the adoption of domestic low carbon or energy-efficient innovations are wide ranging (Bale et al., 2013; Mcmichael and Shipworth, 2013; Southwell and Murphy, 2014) as well as digital innovations (see Dedehayir et al., 2017). With a multitude of research discovering the importance and effectiveness of interpersonal communication for encouraging adoption, non-adopters connected to early adopters in their social networks benefit from receiving persuasive interpersonal information (Peres, 2014; Yamamoto, 2015).

H_1 - Interpersonal communication channels are important sources of information for non-adopters of energy-SHTs

H_2 - Non-adopters of energy-SHTs are connected to early adopters for interpersonal sources of information

2.4 Communication behaviours

2.4.1 Information seeking

Not only are the sources of information important for the diffusion of innovations, but so are the communication behaviour characteristics of people within the social system. Consumers typically engage in information search activities to understand how products are used and their potential benefits. Literature suggests that finding out more about an innovation can help strengthen positive perceptions for potential adopters (Szmigin and Piacentini, 2015). Wilson et al. (2017)'s survey results on SHTs were consistent with DoI expectations that potential early adopters actively seek information, whilst potential later adopters are expected to be less aware of new technologies and less likely to actively seek information. For those who have already made a decision to adopt, information seeking behaviour continues in a desire to justify the decision (Russell-Rose and Tate, 2013).

H_3 - Early adopters of energy-SHTs actively seek information

2.4.2 Information sharing

Opinion leadership is a term used frequently in marketing literature to describe the characteristic of those who informally influence the attitudes or behaviours of others by means of innovation-related conversations (Stern and Gould, 1988) and is considered to be a trait of early adopters (Dedehayir et al., 2017). Typical characteristics of opinion leaders include being well connected, knowledgeable, trusted, and persuasive (Gladwell, 2009). Their societal position and status mean that they are able to reassure others that something works as intended, share experience and knowledge and reduce perceived risks amongst non-adopters (Raj, 2018). They are considered to be critical to the success of new innovations as they provide interpersonal, informal, and verbal advice and direction for search, purchase and innovation use (Flynn et al., 1996).

H_4 - Early adopters of energy-SHTs have a high degree of opinion leadership for energy-SHTs

To accelerate innovation diffusion, early adopters with opinion leadership traits are required to be easily accessible and strategically positioned to reach others in a given situation (or condition) (Valente, 2010). With digitalisation, there is a growing body of literature on the importance of internet communication through social media and website reviews (e.g. Abdallah et al., 2017). Such platforms offer the opportunity to share experiences and knowledge with a wide audience. Early adopter characteristics have developed since Rogers' (2003) descriptions, and an additional perspective to assess whether someone is easily accessible is to examine their frequency and use of online social media (Szmigin and Piacentini, 2015; Weeks et al., 2015). With SHTs being digital themselves, such an assessment offers an insight into a highly applicable characteristic.

H_5 - Early adopters of energy-SHTs are active social media users

2.4.3 Communication network

The positive communication of an innovation has the potential to lead others to adopt (Southwell and Murphy, 2014). Two mechanisms limit or aid the self-sustaining word-of-mouth for a new technology: density of interpersonal communications (structural characteristics) and the relevance of information (functional characteristics) (Dattée and Birdseye, 2007).

Firstly, the density of interpersonal communications (the number of people information is exchanged with), is related to the well-known network theory of Granovetter's (1973) strength of weak ties. Granovetter (1973) concludes that it is weak ties which provide the best potential sources of novel information, and therefore the most beneficial scenario for supporting diffusion is for communication to occur across a high density of weak ties.

H_6 - Early adopters of SHTs communicate about SHTs with a high density of people

H_7 - Early adopters of SHTs communicate about SHTs with a high density of weak ties

Secondly, the relevance of information exchanged bears an influence on its successes. A study by Axsen et al. (2018) on communication around electric vehicles in Canada explains that some early adopters might emphasise motivations that do not resonate well with certain mainstream consumers. Axsen et al. suggest such people may be better at communicating about functional aspects (i.e., cost savings, convenience and quality) which is where specialist media tend to be more influential anyway. In contrast, information from early adopters about their perceptions and motivations might only be effective with mainstream consumers in certain lifestyle groups. The ability to judge the relevance of information shared is one which is considered to come easily to opinion leaders (Richmond, 1977), however, if an early adopter is not an opinion leader, they may only generate information to pragmatists who will discount its relevance, disregarding it as technology hype, and thus hindering diffusion.

A report produced from a survey of the UK population, suggests non-adopters of SHT are aware of SHTs, but there is a lack of knowledge regarding the technology's capabilities, how they can help and why they are needed (YouGov, 2018). There is a need for adopters to share information regarding the advantages of SHTs to help improve perceptions of these emerging technologies (Hargreaves and Wilson, 2017). Palm (2017) found that knowledge transferred through interpersonal channels was rather basic and mainly of functional how-to information, but was nevertheless perceived as useful, reducing uncertainties and contributing to persuade the participants to adopt an innovation. Hargreaves et al. (2018) suggest that smart features of new technologies may result in demanding, time-consuming learning and require forms of adaptation from householders that may limit their use. Advice and explanations from current adopters on practical, how-to information is necessary.

H_8 - Early adopters of SHTs communicate about functional aspects of SHTs (relative advantage, complexity and compatibility)

Through reviewing the literature and relevant concepts within the theory of DoI, it is evident that early adopters are crucial for helping non-adopters to overcome decision barriers and encourage adoption. As market reports show energy-SHTs are stuck in a niche market, it is essential to collect data on adopters and non-adopters to provide insights as to whether current adopters are fulfilling their role within the diffusion process, and if not, which elements need to be addressed to help achieve greater rates of adoption for energy-SHTs.

3. Method

In order to tackle the research question 'how can the adoption of energy-SHTs be encouraged through social mechanisms?', we compare data collected from current adopters (regarded as the early adopters) and non-adopters of three energy-SHTs (Smart lighting, Smart heating systems and Smart appliances) to test our hypotheses. Figure 1 below illustrates how the hypotheses and elements of Rogers' (2003) DoI framework are linked, with the flow of information through communications channels leading to diffusion.

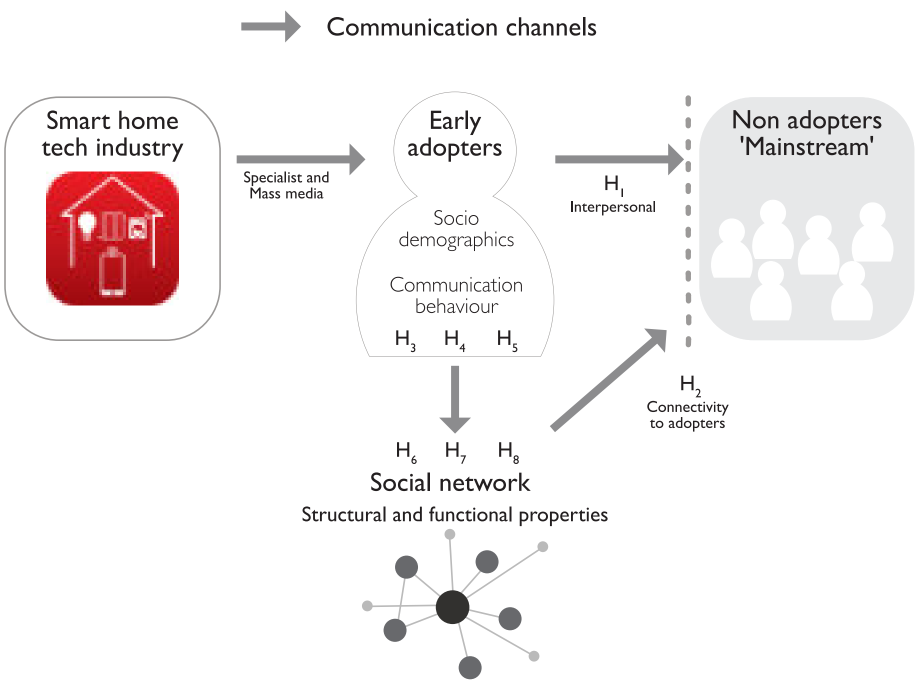


Figure 1. Summary of hypotheses and elements of the DoI framework.

3.1 Instrument design

An online survey was designed in Qualtrics (www.qualtrics.com) consisting of nine sections (Table 1), the first of which asked 'Have you ever had … at home?' and provided four response options: 1) yes, currently; 2) yes, in the past; 3) no, but I've heard of them; and 4) no, I have never heard of them. If a respondent stated they had never heard of it, they were not presented questions regarding that specific energy-SHT. If someone had not heard of all three, they were exited from the survey.

Table 1. Outline of nine topics, example questions for the online survey.

#	TOPIC	QUESTION EXAMPLE
1	Energy-SHT adoption	Have you ever had [smart lighting] at home?
2	Opinion of and propensity towards energy-SHTs	How likely are you to have [smart lighting] within the next year?*
3	Communication channels	How important have these sources of information been in shaping your opinion of smart home technologies?
4	Innovation information	To what extent have you actively sought information about smart home technologies?
5	Social network	Roughly how many close friends would you say you have?
6	Exposure to other adopters	Have any of the following people ever had smart home technologies?
7	Communication on energy-SHTs	Roughly, how many people would you say you have spoken with (in person or via phone/internet) about any of these smart home technologies in the last 6 months?
8	Personal characteristics	How many hours do you spend on social media on a typical weekday?
9	Socio-demographics	What is the highest level of education you have completed?

*Non-adopters and past adopters asked

To reduce misinterpretation of the type of SHTs we were interested in, infographic representations and descriptions were provided (Figure 2), emphasising which technologies were not included, such as smart phones and programmable wall-mounted thermostats. As participants self-reported their adoption status, we were unable to detect false negatives (adopters claiming to be non-adopters) but in order to identify false positives, those who reported being adopters were then asked to provide the name of their product.

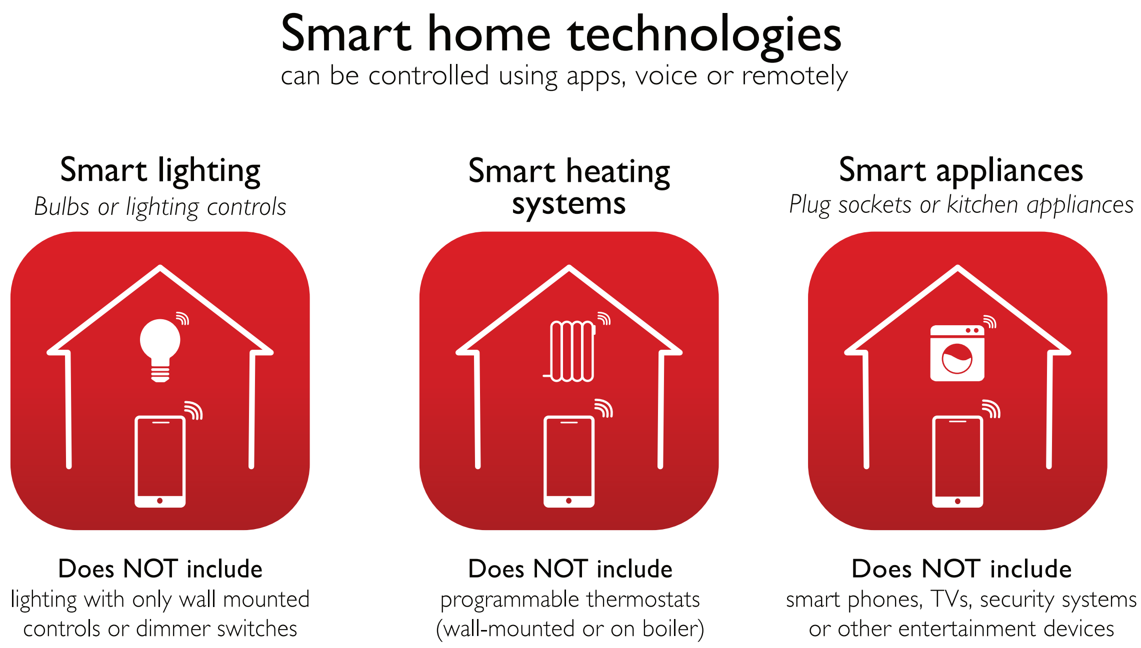


Figure 2. Infographic shown to participants to explain the three energy-SHTs.

For other survey topics, items were based on established precedents from the literature for constructs of social networks (mirroring large population surveys such as the General Social Survey) and opinion leadership (Goldsmith and De Witt, 2003), with slight modifications to fit the context of this research. The full survey instrument is available as supplementary material in Appendix A. Many of the questions used a five-point Likert scale, from *strongly disagree* to *strongly agree*. Care was taken to minimise variation of wording between the questions asked of adopters and non-adopters to allow for comparability.

Participants' social network characteristics were collected using methods from the discipline of social network analysis, providing empirical tools for capturing the social context in which innovations are adopted and diffused (Kolleck, 2013). Questions asked how many close friends and other social contacts (weak ties) the participant had, followed by a name generator (Crossley et al., 2015, p. 50) requiring the participant to provide up to five names of close friends, along with information about them and their relationships between each other. This methodology is used by many large population surveys and was deemed sufficient for the purpose of this study. However, it is well documented that social network surveys can be time consuming, and lead to cognitive burden and respondent fatigue, especially when collecting data on relationships between friends to assess the structure of a network (Borgatti et al., 2018; Crossley et al., 2015). To reduce such issues, an interactive and visually engaging interface was incorporated into the survey, using a similar concept to Stark and Krosnick (2017). Taking advantage of Qualtrics' ability to incorporate Javascript code enabled a tailored close friend network to be displayed as 'click and drag' bubbles which could be linked together by the participant to report friendship connections (Figure 3).

Additional questions in Topic #7 'Communication on energy-SHTs' were asked of participants who indicated they had spoken with at least one person about energy-SHTs to discover greater detail regarding how many of those spoken to were close friends or weak ties, as well as communication topic frequency on a five-point Likert scale from *never* to *always*.

A pilot survey was conducted, with question order and wording revised following feedback to improve flow and comprehension of the survey.

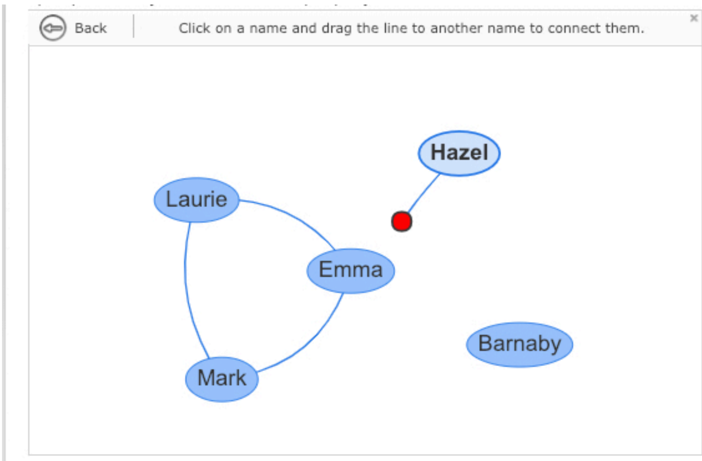


Figure 3. Example screenshot of interactive survey question collecting friendship connections within a participant's social network.

3.2 Data collection

A non-representative convenience sample of 822 UK respondents were recruited online through two distinct methods between 19th May and 2nd July 2019. To collect an over-representative sample of SHT adopters, the first method utilised social media platforms, placing posts and adverts linking to the online survey and offering a prize draw incentive for survey completion. Contacts from SHT industry tradeshows and exhibits provided suggestions for webpages to administer and target SHT adopters. To target non-adopters, the second method utilised non-probability quota sampling with Qualtrics' opt-in panels. Average completion time across both finalised samples was 11 minutes 23 seconds.

3.3 Data analysis

Survey results were downloaded from Qualtrics as a csv file, cleaned and quality checked. A total of 109 respondents were removed from the dataset for being speeders, straight-liners (identified and verified by attention checking questions) or for providing nonsensical text in the open responses. Of the remaining 713 high quality respondents, 28 were identified as false positives for their adoption status and were therefore reallocated as non-adopters. Analyses were conducted in SPSS v25. To account for the two data collection methods used, an additional variable 'recruitment' was created to identify the method a participant had been recruited through and then placed as a control in the analysis models. To test hypothesis H_1, a paired-samples t-test was used to determine whether there was a statistically significant mean difference between the importance of information sources for non-adopters. The difference scores for the importance of interpersonal communication and specialist and mass media were normally distributed, as assessed by visual inspection of a Normal Q-Q Plot.

The remainder of the hypotheses (H_2-H_8) were tested using either chi-squared, Mann Whitney U tests or independent-samples t-tests depending on the variable type (ordinal, nominal or continuous) and whether the results met the statistical assumptions required to perform parametric analysis. Such statistical methods allowed us to assess whether differences existed between current adopters and non-adopters. For statistically significant results, effect sizes were calculated for the independent-samples t-tests using Hedge's G (to account for the unequal group sizes), Cohen's d for the paired-samples t-test and phi for the chi squared tests (Ellis, 2012).

3.3.1 Social networks analysis

Information collected on respondents' social networks did not require specialist software for analysis. Microsoft Excel was used to calculate values for network density, homophily, and transitivity (also known as clustering) (Crossley et al., 2015) before incorporating results into an SPSS dataset containing all other survey data. Network density is simply the number of actors reported in a participant's network. To calculate homophily scores for each participant's close friend network, those indicated as household members were first excluded due to an increased likelihood of being heterophilious in age (spanning generations) and gender (partners commonly of the opposite sex). Household income would also be the same as the participant. Homophily scores were calculated as an EI Index (Borgatti et al., 2009, p. 274) for age, household income and gender, ranging between -1 (perfect homophily whereby all actors in a social network are the same), and +1 (perfect heterophily, whereby all actors are different). Transitivity was calculated using a matrix term described in Borgatti et al. (2009, p. 156). Higher values indicate greater clustering, in other words, close friends of a participant were also close friends with each other.

3.3.2 Connectivity to early adopters analysis

A new variable was calculated to represent an overall level of connectivity to early adopters for interpersonal sources of information in order to test H_2 "Connectivity to early adopters". A 2-step cluster analysis with likelihood distance was used to group participants based on their response to six questions regarding whether or not they knew others in their social networks who had adopted energy-SHTs. This method was chosen as it allows both continuous and categorical variables to be used. The two continuous variables were standardised before running the analysis. Results produced two distinct clusters: ‘low connectivity’ and ‘high connectivity’ to potential interpersonal sources of information regarding energy-SHTs, with 71.2% and 28.8% of all participants in the respective clusters. A chi-square test for association was then conducted between adopter status (adopter, non-adopter) and interpersonal connectivity to early adopters (low, high).

3.3.3 Opinion leadership analysis

To measure underlying constructs of opinion leadership, a well-established six-item scale was used (Goldsmith and De Witt, 2003; Kim, 2007). The scale results from the survey had a high level of internal consistency, as determined by a Cronbach's alpha of 0.769. Item 6, 'My opinion on them [SHTs] seems not to count with other people’ had a low value of 0.253 for the squared multiple correlation, and the highest rate of ‘don’t know’ responses, indicating low reliability. By removing it from the scale, Cronbach's alpha increased to 0.809, thus increasing the level of internal consistency. Following precedents, principle component analysis (PCA) followed by varimax orthogonal rotation was used in SPSS to reduce the scale (Goldsmith and De Witt, 2003). The suitability of PCA was assessed prior to analysis. Inspection of the correlation matrix showed that all variables had at least one correlation coefficient greater than 0.3. The overall Kaiser-Meyer-Olkin (KMO) measure was 0.744 with individual KMO measures all greater than 0.6, classifications of 'mediocre' according to Kaiser (1974). Bartlett's test of sphericity was statistically significant ($p < .001$), indicating that the data was likely factorizable. The analysis revealed two components that had eigenvalues greater than one and which explained 57.7% and 24.4% of the total variance (82.2% in total). Strong loadings were found for 'influence' items on Component 1 and 'advice' items on Component 2, maintaining consistency with the personality attributes the scale was designed to measure. Together, the two components were used to test our hypothesis H_4 “Opinion leadership”.

3.3.4 Social media activity analysis

Results from three questions relating to social media use (hours spent using, hours spent communicating and total number of types) were used to create a variable termed ‘social media activity’ in order to investigate whether H_5 “Social media activity” holds. To overcome issues of missing data and uneven distribution of participants and input predictor importance, K-means clustering was used, stating two clusters to be formed. This produced two equally split groups with greater results for separation and cohesion. A chi-square test for association was conducted between adopter status and social media activity.

3.3.5 Binomial logistic regression

Characteristics tested through our hypotheses and found to be significantly different between adopters and non-adopters helped develop a composite picture of energy-SHT adopters. Binomial logistic regression was performed to: ascertain the effects of the various characteristics on the likelihood that participants are adopters of energy-SHTs; control for overlapping effects; and examine which hypotheses remain robust when all other variables are held constant. Forward conditional stepwise selection of variables was used for each of the four blocks of variables, with each model incorporating an additional block: i. socio-demographics, ii. social network characteristics, iii. communication channels, iv. communication behaviours. Linearity of the continuous independent variables with respect to the logit of the dependent variable 'adopter status', were confirmed via the Box-Tidwell procedure.

4. Results

4.1 Participant characteristics

The sample of 673 participants consisted of 313 current adopters and 360 non-adopters[1]. Table 2 summarises the descriptive results for each variable used in the statistical analyses reported, separating the data by adopter status.

The adopters were more likely to be 35-54 years old and had higher levels of household income than non-adopters. Such socio-demographics correspond with findings from market research regarding adopters of SHTs (e.g. Mintel, 2018). Other key points worth noting about the adopter sample include: they use more new technology and apps; have a higher propensity to adopt additional energy-SHTs and have a more positive opinion of energy-SHTs compared to the non-adopter sample (Table 2).

[1] Data from 40 past-adopters was excluded from analysis, as the focus of this paper is on the role of current-adopters in the diffusion process.

Table 2. Descriptive results for adopters and non-adopters of energy-SHTs.

		Adopters		Non-adopters	
Variable		Frequency	Percentage	Frequency	Percentage
Gender	Female	112	36.0	203	56.7
	Male	199	64.0	155	43.3
Age	18-34	111	35.7	115	32.1
	35-54	149	48.0	107	29.8
	55+	51	16.4	137	38.2
Education	No qualifications	3	1.0	22	6.2
	GCSE or O-Levels	39	12.7	67	19.0
	Post-secondary, non-tertiary	108	35.3	116	32.9
	Undergraduate degree or higher	156	51.0	148	41.9
Household income	<=£24,999	57	19.3	137	43.2
	£25,000 - 39,999	76	25.8	75	23.7
	>=£40,000	162	54.9	105	33.1
Connectivity to adopters	High connectivity	122	40.0	63	18.6
	Low connectivity	183	60.0	275	81.4
Social media activity	High activity	191	61.2	145	40.4
	Low activity	121	38.8	214	59.6
		Mean	SD	Mean	SD
Social network	# close friends (strong ties)	9.16	21.57	5.94	6.44
	# other social contacts (weak ties)	81.00	214.70	58.98	125.96
	Gender EI index	0.56	0.56	0.62	0.51
	Age EI index	-0.14	0.73	-0.04	0.74
	Household income EI index	0.12	0.72	0.26	0.71
	Transitivity (network clustering)	0.41	0.34	0.35	0.33
Communication Channels	Specialist and mass media	3.25	0.96	2.61	1.05
	Interpersonal	3.38	1.15	2.89	1.28
Communication behaviour	Information seeking	2.51	0.71	1.47	0.76
	Opinion leadership - influence	0.48	0.89	-0.47	0.88
	Opinion leadership - advice	0.20	1.00	-0.20	0.97
Communication on energy-SHTs	Communication density	7.66	14.83	2.01	7.11
	% of comms. with weak ties	50.63	34.66	45.10	39.93
	Frequency of relative advantage	3.07	1.13	2.58	1.23
	Frequency of compatibility	3.06	1.16	2.66	1.21
	Frequency of complexity	3.31	1.16	2.62	1.09
Personal Characteristics	Use new tech and apps	3.88	0.96	2.71	1.21
	Try to save energy	3.90	0.96	3.63	1.16
	Average adoption propensity	59.33	26.17	35.37	29.09
	Opinion of energy-SHTs	4.17	0.63	3.52	0.85

4.2 Social network characteristics

Overall, adopters reported larger social networks (Table 2) but no significant differences were found between adopters' and non-adopters' social network density for close friends or weak ties. Results from independent-sample t-tests revealed no significant differences between adopters' and non-adopters' homophily scores for age or gender. However, household incomes of close friends were significantly more homophilious for adopters (0.12) than non-adopters (0.26), $p<.05$, $g = 0.19$ (small effect). Close friend social networks were also found to be significantly more clustered for adopters (0.41) than non-adopters (0.35), $p<.05$, $g = 0.18$ (small effect).

4.3 Communication channels – information sources

Results from a paired-samples t-test on the importance of information sources for shaping opinions of energy-SHTs revealed that for non-adopters, interpersonal channels elicited a statistically significant mean greater in importance compared to specialist and mass media, $p<.001$, $d = 0.25$ (small effect). H_1 "Interpersonal" is therefore confirmed.

Chi-square test results indicated a significant association, $\chi^2(1) = 35.70$, $p<.001$, $\phi = 0.24$ (small effect) between adopter status and connectivity to early adopters. Non-adopters were 2.91 times more likely than adopters to have low connectivity to adopters, indicating the opposite of our postulated hypothesis H_2. Our results consequently reject H_2 "Connectivity to early adopters". Of the 58 non-adopters who stated they actively seek information, 62% also stated friends, family and colleagues are important or very important sources of information. Chi-square reveals a significant association between the two variables, $\chi^2 (1) = 26.3$, $p<0.001$. Such results strengthen the argument that social networks are important sources of information as those who are actively seeking information go to friends. However, as our results found non-adopters to have low interpersonal connectivity to adopters, this implies they are potentially either getting information from other non-adopters, reinforcing their decision not to adopt, or a limited number of adopters in the social networks are not effective at persuading them to adopt.

4.4 Communication behaviours

An independent-samples t-test found information seeking behaviour amongst adopters (2.51) was significantly higher than non-adopters (1.47) $p<0.001$, $g = 1.41$ (large effect), confirming the hypothesis H_3 "Seek information".

Interpretation of the adopters' opinion leadership results show that the advice component, which consisted of statements around whether others seek advice from them, had lower levels of agreement than statements in the influence component (Table 2). Nevertheless, independent-sample t-tests found significant differences between adopters and non-adopters, with adopters scoring higher for both opinion leadership components - 'influence' ($p<.001$, $g = 1.08$, large effect) and 'advice' ($p<.001$, $g = 0.41$, small effect). Considering results for both components, H_4 "Opinion leadership" was confirmed.

A chi-square test indicated a significant association between adopter status and social media activity, $\chi^2(1) = 28.97$, $p< .001$, $\phi = 0.208$ (small effect). Adopters were found to be 2.33 times more likely to have high social media activity compared to non-adopters, thus eliciting them to be more socially accessible and resulting in H_5 "Social media users" being confirmed.

Responses for communication network density were shown by an independent-sample t-tests to be significantly different between adopters and non-adopters, $p<.001$, $g = 0.5$ (medium effect), with averages of 7.66 people and 2.01 people being spoken to respectively. This result confirms our H_6 "Communicate density". When interpreting these results, it is worth noting that a high percentage of respondents had not spoken to anyone about SHTs over the last six months, including two-thirds of non-adopters and over a fifth of adopters.

Results on communication with weak ties were represented as a percentage of the total number of people spoken to. An independent t-test found no significant difference between adopters' and non-adopters' weak tie communication densities, leading to the rejection of H_7 "Communicate weak ties". Overall, non-adopters did speak to slightly less weak ties, going more to strong ties to talk about energy-SHT.

Regarding the conversation topics investigated, adopters spoke most frequently about SHTs' ease of use, whilst non-adopters reported speaking most frequently about how compatible SHTs are with daily life (complexity and compatibility respectively in Table 2). Independent t-tests showed that adopters significantly communicate more frequently than non-adopters on all three functional aspects of SHTs (relative advantage $p<.001$, compatibility $p<.005$, complexity $p<.001$), confirming H_8 "Communicate functional".

Participants were provided an opportunity to offer further detail about their conversation topics, with 73 participants completing the open-ended question (45 adopters and 28 non-adopters). Responses predominantly consisted of comments about private functional attributes, with general know-how information such as controllability, ease of set up and use being most frequently stated by non-adopters e.g. "*A lot of the conversations have been about… whether they make your life easier. Some … seem to complicate life if they are not used or explained properly*". Whilst adopters regularly mentioned value for money - "*I've had many conversations with close friends…if they are worth the money or just a fad*". Of all the comments, less than a fifth were negative (18%).

Table 3 below summarises which hypotheses were confirmed by our survey results.

Table 3. Summary of analysis for communication channels and behaviour.

Hypothesis	Hypothesis label	Test result
H_1 Interpersonal communication channels are important sources of information for non-adopters of energy-SHTs	Interpersonal	Confirmed
H_2 Non-adopters of energy-SHTs are connected to early adopters for interpersonal sources of information	Connectivity to adopters	**Rejected**
H_3 Early adopters of energy-SHTs actively seek information	Seek information	Confirmed
H_4 Early adopters of energy-SHTs have a high degree of opinion leadership for energy-SHTs	Opinion leadership	Confirmed
H_5 Early adopters of energy-SHTs are active social media users	Social media activity	Confirmed
H_6 Early adopters of energy-SHTs communicate about energy-SHTs with a high density of people	Communicate density	Confirmed
H_7 Early adopters of energy-SHTs communicate about energy-SHTs with a high density of weak ties	Communicate weak ties	**Rejected**
H_8 Early adopters of SHTs communicate about functional aspects of SHTs (relative advantage, complexity and compatibility)	Communicate functional	Confirmed

4.5 Distinctive adopter characteristics

Binomial logistic regression models were used to test the effects of different variables on the likelihood that participants are an adopter of energy-SHTs. Exp(B) values in the models show the odds ratios, which explain how a specific variable increases or decreases the likeliness of being an early adopter. Moreover, the pseudo R^2 values account for the variance of being an early adopter versus being a non-adopter. The higher the pseudo R^2, the more variability explained, and the better the model.

Model 1 considered socio-demographics and recruitment method variables, removing education and the recruitment variable which were not significant to $p<0.05$. Model 1 correctly predicted 65.8% of cases. Model 2 included the significant variables from Model 1 and analysed the two significantly different social network variables within the adopter and non-adopter categories identified in Section 4.2. Neither homophily wealth nor network clustering were retained in the model. Model 3 continues building on the previous two models, considering the communication channel variables. Only the variable 'connectivity to adopters' was added, with the model predicting 68.9% of cases. Model 4 then incorporated the final block of significant communication behaviour variables from Section 4.3. All but 'social media activity' were retained. Model 4 explains 53.4% (pseudo R^2) of the variance in adopter status and correctly classifies 79.5% of cases (Table 4). Communication behaviour variables were found to be more significant than other blocks of variables, with information seeking behaviour being the strongest significant predictor of adoption status controlling for the effect of other variables. The significant variables in Model 4 all conform to DoI expectations regarding early adopter characteristics. Of the variables found to not coincide with expectations (Table 3), 'connectivity to adopters' was the only one to be a significant predictor of adoption status in Model 3 – when controlling for sociodemographic, social network and communication channel variables.

Table 4. Binary logistic regression model results.

	Model 1		Model 2		Model 3		Model 4	
Variables	Exp(B)	p-value	Exp(B)	p-value	Exp(B)	p-value	Exp(B)	p-value
Gender	.471	**.001***	.471	**.001***	0.466	**.001***	.741	.237
Age 18-34		**.001***		**.001***		**.001***		.399
Age 35-54	2.649	**.001***	2.649	**.001***	2.328	**.002***	.805	.531
Age 55+	2.839	**.001***	2.839	**.001***	2.659	**.001***	1.203	.587
H. income <= £24,999		**.001***		**.001***		**.001***		.020
H. income £25,000 - £39,999	.268	**.001***	.268	**.001***	.312	**.001***	.497	**.024***
H. income £>=40,000	.866	.562	.866	.562	.968	.899	1.177	.594
Education[a]								
Recruitment[a]								
EI wealth[a]								
Clustering[a]								
Specialist and mass[a]								
Interpersonal[a]								
Connectivity to adopters					.424	**.001***	.823	.530
Seek information							2.186	**.001***
Opinion leadership – influence							1.767	**.001***
Opinion leadership – advice							1.389	.024
Communication density							1.101	**.006***
Social media activity[a]								
Pseudo R^2	0.198		0.198		0.230		0.534	

[a]Variables omitted
*p<.01

5. Discussion

Our empirical study of energy-SHTs adopters and non-adopters found that the social networks of adopters were more clustered with greater homophilious wealth. Adopters not only actively seek information and construct their opinion of energy-SHTs from a range of sources, they also self-reported as being opinion leaders and influencing others. They expressed greater positivity and propensity towards further adoption and were more active on social media compared to non-adopters. Overall, adopters communicated about energy-SHTs with more people than non-adopters, but not especially more weak ties. Non-adopters on the other hand, were found not to be information seekers and shaped their opinions on energy-SHTs from interpersonal sources of information. However, their social networks contained few adopters, reducing their exposure to first-hand experience and knowledge.

5.1 Implications from the diffusion of innovations theory

A core element of DoI focusses on social influence and social network processes (Rogers, 2003; Rogers et al., 2005). However, despite this, such elements are often missing from many studies of diffusion (for example in economics and psychology research which place greater focus on innovation attributes and adopter characteristics). Furthermore, the majority of DoI's theorising was conducted in the pre-internet era, and therefore the drastic changes occurring with digitalisation shifting how information is spreading amongst social networks are not included in such original works.

Through empirically testing hypotheses derived from the literature, our results show that DoI still holds for early adopters of energy-SHTs. The binary logistic regression models established from our significant results (Table 4) highlight the importance of communication channels and behaviours with such variables being the strongest predictors of adoption status. The two hypotheses rejected by our results (Table 3) identify which elements of the theory do not conform to expectations, providing insights into potential barriers in the diffusion process. In other words, empirically discovering social factors potentially inhibiting the spread of information and contributing to the theoretical 'chasm' (Moore, 2014) for energy-SHTs.

This paper not only highlights the use of social network analysis methods for the identification of potential 'chasmic' barriers to diffusion for energy-SHT market, our results also expand beyond the SHT domain, providing insights for broader sets of low carbon consumer technologies struggling to overcome the chasm. A meta-analysis of 130 environmental innovations by Clausen and Fichter (2019) revealed groupings based on similarities of characteristics and diffusion (or lack of). The research presented in this paper complements such work by identifying social barriers which are theoretically relevant to particular subsets of innovations with similar attributes, early adopter characteristics and social communication salience i.e., those with strong digital characteristics particularly in the home. The strategies presented in Section 5.2 target the barriers identified by our results and are relevant for other innovations suffering from similar obstacles.

5.2 Encouraging adoption into the mass market

To help encourage the adoption of energy-SHTs in support of climate change and other energy system benefits, targeted strategies can be derived from theoretical discussions of transition dynamics and a range of social network interventions to tackle the two identified barriers: 1) adopters not substantially spreading messages beyond their own wealthy clustered close social networks, thus restricting diffusion and limiting the seeding of information amongst weak ties, and 2) non-adopters having low connectivity to adopters resulting in their requirement for interpersonal information not being met through their social networks.

Acknowledging that a multitude of meso-level actors and processes provide crucial roles in sustainable transitions , in our work, we focus on the meso-level layer of early adopters and their social networks[2]. Important functions provided by intermediaries include information gathering and dissemination, fostering networking and partnerships, and technical consulting (Kanda et al., 2018; Kivimaa et al., 2019), we make the analogy that early adopters have the capability to fulfil similar intermediary roles through various interventions.

5.2.1 Strategies to encourage adopters to share information with weak ties

Social network interventions have most widely been used to tackle health-related issues (Hunter et al., 2017; Valente, 2012), but have gained momentum in marketing campaigns to spread trusted messages about specific products (Gladwell, 2009; John et al., 2017). In the domain of digital home innovations many on-line forums exist for sharing technological know-how but are often only frequented by adopters. Such virtual communities provide information (not available from other market actors) about the workings of the technology (Hyysalo et al., 2018), building and developing knowledge from a wide variety of participants, creating a community across geographical boundaries and contextualising innovations in a local environment for many (Meelen et al., 2019). Despite delivering such intermediary functions, in order to upscale to the mass market, adopters need to communicate and spread less technical information externally to other platforms with wider audiences.

To catalyse and facilitate the mobilisation of adopters to share information with non-adopters in their social networks, the industry could identify online opinion leaders (reviewed by Wang, 2017), for example Instagram influencers (Casaló et al., 2018), taking advantage of adopters' high social media activity. With the internet providing endless sources of information, consumers increasingly rely upon practical shortcuts and recommendation mechanisms to make decisions (Webster, 2014). Early adopter social media influencers act as intermediaries in consumer cultures and markets, developing trust and credibility in and through social networks to identify reliable products (Podkalicka, 2019). For such strategies, trust is a significant factor needing to be considered as it mediates the social influence of a message and can vary depending on the platform used and who is interacting with who e.g. product reviews, blogs or platforms such as Facebook (Byrum, 2019).

[2] Other intermediary actors in the energy and eco-home literature include businesses and community organisations (e.g. Bergek, 2020; Mignon and Kanda, 2018), and professionals such as energy efficiency advisers or technology installers (e.g. Owen and Mitchell, 2015).

5.2.2 Strategies to connect non-adopters and adopters

Non-adopters in our study reported low connectivity with adopters. This can be interpreted as either non-adopters not having adopters in their social circles or that non-adopters are not aware that members of their social network are indeed adopters.

To tackle the latter interpretation, traditional strategies such as Brownie Wise's 'Tupperware Party' method (Clarke, 2014) could help reach non-adopters and provide visual, interactive learning within friendship groups. Pettifor et al. (2015) found information alone to be insufficient for encouraging homeowners to make major renovations, therefore providing opportunities to demonstrate and provide hands-on experience through such 'Party' concepts, could be more effective for some non-adopters. Such demonstrations could also provide an opportunity to increase awareness for improved energy management as actual energy benefits of SHTs depends not only on whether consumers know about, and care about the energy benefits, but also how they use their products (Sanguinetti et al., 2018).

To connect adopters with non-adopters from outside their social networks, the concept of 'eco open homes' could be used to perform a more formal intermediary role, providing a space for showcasing and disseminating learning, as well as networking at the community level (Kivimaa et al., 2019; Martiskainen and Kivimaa, 2018). Such meso level networks comprise of homeowners with a range of low carbon innovations, from energy efficiency improvements to electricity generation (Energy Saving Trust, 2019), however rarely include adopters of energy-SHTs. This presents an opportunity to expand upon such concepts, benefiting from the multiple functions formal intermediaries can play in the diffusion of energy-SHT and thus transition to sustainable homes.

For the above initiatives to be successful, interest is still required from non-adopters for effective engagement. Sanguinetti et al. (2018)'s research on adoption barriers to home energy management systems showed that unique demographic and psychographic profiles exist amongst consumers at different stages of the adoption decision process, suggesting certain strategies should consider adaptations and further targeting to specific consumer groups.

In general, our results revealed positive opinions towards energy-SHTs amongst UK non-adopters, but low adoption propensity and low information seeking behaviour. Encouraging conversations around the additional beneficial attributes energy-SHTs bring to users that are less widely known, could help expand interest. With the current phenomenon occurring amongst members of society making behavioural changes for climate change motives (Söderberg and Wormbs, 2019), such growing trends amongst certain consumer groups indicate that attention on attributes of environmental benefits could be positively linked to SHT uptake and help to engage additional audiences outside the realm of the technophiles.

5.3. Further research

The research presented in this paper focusses on the role of social elements within a system and the communication behaviours of individuals. Yet, DoI theory includes other aspects which facilitate or impede an innovation's rate of diffusion. Innovation attributes, contextual and situational factors, external influences such as government policy and the market, all have the potential to impact diffusion (Rogers, 2003). As our findings on communication behaviour and individuals' social contexts inter-relate with these additional aspects, it is essential to situate these findings alongside other models which focus on other individualistic elements such as attributes and adopter characteristics (e.g. Whittle et al., 2020), followed by the consideration of wider contextual models (e.g. Grubler et al., 2018) to build a holistic theoretical framing. By linking our findings with various other models and theories will help enable the integration of the complex elements needing to be considered for a sustainable transition e.g. society, technology, the economy and the environment (Hirt et al., 2020).

Building upon the research presented here, a wealth of opportunities exist to apply social network theories and methodologies to gain further insights into diffusion processes of low carbon innovations. We recommend qualitative interviews to be conducted with adopters to collect data on wider social network structure and characteristics, investigating whether traits such as clustering and homophily wealth found in this study's sample are indeed characteristics in personal whole networks and thus contributing to the current delay in diffusion. Interviews can also provide the opportunity to gather finer details on communication behaviour, including information exchanged or withheld, with who and in what structural context (e.g. online, coffee lounge at work, at the bus stop). Additional research would greatly benefit from a longitudinal approach, gaining further insights through mapping changes over time amongst the adopter and non-adopter sample, in order to make comparisons with Roger's suggestions for accelerating adoption, that are scientifically valuable.

6. Conclusion

A wide range of factors influence the success or failure of an innovation, with scholars advocating the key role social networks play in diffusion. With the urgent need to radically transform domestic energy use - reducing demand and increasing efficiency - new digital technologies provide an opportunity to enable a smarter and more flexible system. Using DoI as a framework, this research investigated the social networks and communication channels and behaviours of both adopters and non-adopters of energy-SHTs, to discover which social mechanisms are required to encourage uptake in the mainstream market. Results identified the characteristics of early adopters which do not conform to DoI expectations, suggesting potential barriers to the diffusion process. We highlight the need to focus strategies on increasing non-adopters' exposure to interpersonal channels of communication and to encourage early adopters to spread information regarding energy-SHTs beyond their close friendship groups.

Acknowledgements

This work was supported by ERC Starting Grant #678799 for the SILCI project (Social Influence and disruptive Low Carbon Innovation). The authors thank Andrew Brooke for developing the interactive survey tool for gathering network data, Guillaume Favre for providing helpful guidance for the social network analysis, the survey participants for their time and insights into energy-SHT adoption.

Appendix A

The full online survey is provided in Supplementary material https://ars.els-cdn.com/content/image/1-s2.0-S2210422420301301-mmc1.docx

References

Abdallah, A., Rana, N.P., Dwivedi, Y.K., Algharabat, R., 2017. Social media in marketing : A review and analysis of the existing literature. Telemat. Informatics 34, 1177–1190. https://doi.org/10.1016/j.tele.2017.05.008

Accenture, 2016. Igniting Growth in Consumer Technology 1–15.

Axsen, J., Cairns, J., Dusyk, N., Goldberg, S., 2018. What drives the Pioneers ? Applying lifestyle theory to early electric vehicle buyers in Canada. Energy Res. Soc. Sci. 44, 17–30.

Bale, C.S.E., Mccullen, N.J., Foxon, T.J., Rucklidge, A.M., Gale, W.F., 2013. Harnessing social networks for promoting adoption of energy technologies in the domestic sector. Energy Policy 63, 833–844.

Balta-ozkan, N., Davidson, R., Bicket, M., Whitmarsh, L., 2013. Social barriers to the adoption of smart homes. Energy Policy 63, 363–374. https://doi.org/10.1016/j.enpol.2013.08.043

Barnes, M.L., Lynham, J., Kalberg, K., Leung, P., 2016. Social networks and environmental outcomes. Proc. Natl. Acad. Sci. 113, 6466–6471. https://doi.org/10.1073/pnas.1523245113

Baudier, P., Ammi, C., Deboeuf-Rouchon, M., 2018. Smart home: Highly-educated students' acceptance. Technol. Forecast. Soc. Change 119355. https://doi.org/10.1016/j.techfore.2018.06.043

Berg, J.A., 2009. Core networks and whites' attitudes toward immigrants and immigration policy. Public Opin. Q. 73, 7–31.

Bergek, A., 2020. Diffusion intermediaries: A taxonomy based on renewable electricity technology in Sweden. Environ. Innov. Soc. Transitions 36, 378–392. https://doi.org/10.1016/j.eist.2019.11.004

BIT, 2017. Evaluating the Nest Learning Thermostat, Behavioural Insights Team (BIT). London, UK.

Borgatti, S.P., Brass, D.J., Halgin, D.S., 2014. Social Network Research: Confusions, Criticisms, and Controversies, in: Brass, D.J., Labianca, G. (JOE), Mehra, A., Halgin, D.S., Borgatti, S.P. (Eds.), Contemporary Perspectives on Organizational Social Networks (Research in the Sociology of Organizations). Emerald Group Publishing Limited, pp. 1–29. https://doi.org/10.1108/S0733-558X(2014)0000040001

Borgatti, S.P., Everett, M.G., Johnson, J.C., 2018. Analyzing Social Networks, 2nd ed. SAGE Publications Ltd.

Borgatti, S.P., Mehra, A., Brass, D.J., Labianca, G., 2009. Network analysis in the social sciences. Science 323, 892–895. https://doi.org/10.1126/science.1165821

Burt, R.S., Kilduff, M., Tasselli, S., 2013. Social network analysis: foundations and frontiers on advantage. Annu. Rev. Psychol. 64, 527–547.

Byrum, K., 2019. "Hey Friend , Buy Green ": Social Media Use to Influence Eco-Purchasing Involvement. Environ. Commun. 13, 209–221. https://doi.org/10.1080/17524032.2017.1308404

Casaló, L. V., Flavián, C., Ibáñez-Sánchez, S., 2018. Influencers on Instagram: Antecedents and consequences of opinion leadership. J. Bus. Res. https://doi.org/10.1016/j.jbusres.2018.07.005

Choi, H., Kim, S.H., Lee, J., 2010. Role of network structure and network effects in diffusion of innovations. Ind. Mark. Manag. 39, 170–177. https://doi.org/10.1016/j.indmarman.2008.08.006

Clarke, A.J., 2014. Tupperware: The promise of plastic in 1950s America. Smithsonian Institution.

Clausen, J., Fichter, K., 2019. The diffusion of environmental product and service innovations: Driving and inhibiting factors. Environ. Innov. Soc. Transitions 31, 64–95. https://doi.org/10.1016/j.eist.2019.01.003

Cosar-Jorda, P., R. A. Buswell, Mitchell, V.A., 2019. Quantifying energy demand reduction considering householder willingness to apply measures. Build. Res. Inf. 47, 850–864. https://doi.org/10.1080/09613218.2019.1630245

Coskun, A., Kaner, G., Bostan, I., 2017. Is Smart Home a Necessity or a Fantasy for the Mainstream User ? A Study on Users ' Expectations of Smart Household Appliances. Int. J. Des. 12, 7–20.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Chang. 8, 260–263. https://doi.org/10.1038/s41558-018-0121-1

Crossley, N., Bellotti, E., Edwards, M.G., Koskinen, J., Trammer, M., 2015. Social network analysis for ego-nets. SAGE, Los Angeles.

Darby, S.J., 2019. Communicating innovations: Examples from smart technology retrofits. IOP Conf. Ser. Earth Environ. Sci. 329. https://doi.org/10.1088/1755-1315/329/1/012020

Dattée, B., Birdseye, H., 2007. Dynamics of social factors in technological substitutions 74, 579–607. https://doi.org/10.1016/j.techfore.2007.03.003

Dedehayir, O., Ortt, R.J., Riverola, C., Miralles, F., 2017. Innovators and early adopters in the diffusion of innovations: A literature review. Int. J. Innov. Manag. 21. https://doi.org/10.1142/S1363919617400102

Demiris, G., Rantz, M.J., Aud, M.A., Marek, K.D., Tyrer, H.W., Skubic, M., Hussam, A.A., 2004. Older adults' attitudes towards and perceptions of "smart home" technologies: A pilot study. Med. Inform. Internet Med. 29, 87–94. https://doi.org/10.1080/14639230410001684387

EcoGRID, 2016. EcoGrid EU – A Prototype for European Smart Grids.

Ellis, P.D., 2012. The Essential Guide to Effect Sizes, Statistical Power, Meta-Analysis and the Interpretation of Research Results. Cambridge University Press.

Energy Saving Trust, 2019. Green Homes Network [WWW Document]. URL https://greenhomesnetwork.energysavingtrust.org.uk (accessed 11.20.19).

Eyre, N., Killip, G., 2019. Shifting the focus: energy demand in a net-zero carbon UK. Oxford, UK.

Fell, D., Austin, A., Kivinen, E., Wilkins, C., 2009. The Diffusion of Environmental Behaviours; The Role of Influential Individuals in Social Networks, Report 1: Key Findings.

Flynn, L., Goldsmith, R., Eastman, J., 1996. Opinion Leaders and Opinion Seekers: Two New Measurement Scales. J. Acad. Mark. Sci. 24, 137–47.

Ford, R., Karlin, B., Sanguinetti, A., Nersesyan, A., & Pritoni, M. (2016). Assessing Players, Products, and Perceptions of Home Energy Management. San Francisco, CA: Pacific Gas and Electric.

Ford, R., Pritoni, M., Sanguinetti, A., Karlin, B., 2017. Categories and functionality of smart home technology for energy management. Build. Environ. 123, 543–554. https://doi.org/10.1016/j.buildenv.2017.07.020

GfK, 2017. Tech Trends 2017 - Smart Home [WWW Document]. URL http://www.gfk.com/insights/infographic/tech- trends-2017-smart-home/ (accessed 2.10.20).

Gladwell, M., 2009. The Tipping Point: How Little Things Can Make a Big Difference. Abacus.

Goldsmith, R.E., De Witt, T.S., 2003. The Predictive Validity of an Opinion Leadership Scale. J. Mark. Theory Pract. 11, 28–35. https://doi.org/10.1080/10696679.2003.11501930

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 Res. Soc. Sci. 37, 94–101. https://doi.org/10.1016/j.erss.2017.09.037

Granovetter, M., 1973. The strength of weak ties. Am. J. Sociol. 78, 1360–1380.

Greenough, J., 2016. The US smart home market has been struggling — here's how and why the market will take off. Bus. Insid.

Gruber, H., 2019. Proposals for a digital industrial policy for Europe. Telecomm. Policy 43, 116–127. https://doi.org/10.1016/j.telpol.2018.06.003

Grubler, A., Wilson, C., Bento, N., Boza-kiss, B., Krey, V., Mccollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S. De, Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6

Hargreaves, T., Wilson, C., 2017. Smart Homes and Their Users, SpringerBr. ed. Springer International Publishing Switzerland.

Hargreaves, T., Wilson, C., Hauxwell-baldwin, R., 2018. Learning to live in a smart home. Build. Res. Inf. 46, 127–139. https://doi.org/10.1080/09613218.2017.1286882

Hirt, L.F., Schell, G., Sahakian, M., Trutnevyte, E., 2020. A review of linking models and socio-technical transitions theories for energy and climate solutions. Environ. Innov. Soc. Transitions 35, 162–179. https://doi.org/10.1016/j.eist.2020.03.002

Hittinger, E., Jaramillo, P., 2019. Internet of Things: Energy boon or bane? Science (80-.). 364, 326–328. https://doi.org/https://doi.org/10.1126/science.aau8825

Hong, A., Nam, C., Kim, S., 2019. What will be the possible barriers to consumers ' adoption of smart home services ? Telecomm. Policy 101867. https://doi.org/10.1016/j.telpol.2019.101867

Hsu, C.-L., Lin, J.C.-C., 2016. An empirical examination of consumer adoption of Internet of Things services: Network externalities and concern for information privacy perspectives. Comput. Human Behav. 62, 516–527. https://doi.org/https://doi.org/10.1016/j.chb.2016.04.023

Hubert, M., Blut, M., Brock, C., Zhang, R.W., Koch, V., Riedl, R., 2019. The influence of acceptance and adoption drivers on smart home usage. Eur. J. Mark. 53, 1073–1098. https://doi.org/10.1108/EJM-12-2016-0794

Hunter, R.F., de la Haye, K., Badham, J., Valente, T., Clarke, M., Kee, F., 2017. Social network interventions for health behaviour change: a systematic review. Lancet 390, 47. https://doi.org/10.1016/s0140-6736(17)32982-3

Hyysalo, S., Juntunen, J.K., Martiskainen, M., 2018. Energy Internet forums as acceleration phase transition intermediaries. Res. Policy 47, 872–885. https://doi.org/10.1016/j.respol.2018.02.012

IEA, 2019. Energy Efficiency 2019.

IEA, 2013. Energy efficiency market report. Paris, France.

IPCC, 2018. Global Warming of 1.5°C. Summary for Policymakers.

John, L.K., Emrich, O., Gupta, S., Norton, M.I., 2017. Does "liking" lead to loving? the impact of joining a brand's social network on marketing outcomes. J. Mark. Res. 54, 144–155. https://doi.org/10.1509/jmr.14.0237

Kaiser, H.F., 1974. An index of factorial simplicity. Psychometrika 39, 31–36.

Kanda, W., Hjelm, O., Clausen, J., Bienkowska, D., 2018. Roles of intermediaries in supporting eco-innovation. J. Clean. Prod. 205, 1006–1016. https://doi.org/10.1016/j.jclepro.2018.09.132

Kesicki, F., 2012. Costs and potentials of reducing CO2 emissions in the UK domestic stock from a systems perspective. Energy Build. 51, 203–211. https://doi.org/10.1016/j.enbuild.2012.05.013

Kim, D.K., 2007. Identifying Opinion Leaders by Using Social Network Analysis: A Synthesis of Opinion Leadership Data Collection Methods and Instruments. Mycol. Res.

Kivimaa, P., Hyysalo, S., Boon, W., Klerkx, L., Martiskainen, M., Schot, J., 2019. Passing the baton: How intermediaries advance sustainability transitions in different phases. Environ. Innov. Soc. Transitions 31, 110–125. https://doi.org/10.1016/j.eist.2019.01.001

Kolleck, N., 2013. Social network analysis in innovation research : using a mixed methods approach to analyze social innovations. Eur. J. Futur. Res. 1–9. https://doi.org/10.1007/s40309-013-0025-2

Laidi, R., Djenouri, D., Ringel, M., 2019. Commercial Technologies for Advanced Light Control in Smart Building Energy Management Systems : A Comparative Study. Energy Power Eng. 1–23.

Martiskainen, M., Kivimaa, P., 2018. Creating innovative zero carbon homes in the United Kingdom — Intermediaries and champions in building projects. Environ. Innov. Soc. Transitions 26, 15–31. https://doi.org/10.1016/j.eist.2017.08.002

McKinsey & Company, 2018. There's no place like [a connected] home: perspectives on the connected consumer in a world of smart devices. Industry report.

Mcmichael, M., Shipworth, D., 2013. The value of social networks in the diffusion of energy-efficiency innovations in UK households. Energy Policy 53, 159–168. https://doi.org/10.1016/j.enpol.2012.10.039

Meelen, T., Truffer, B., Schwanen, T., 2019. Virtual user communities contributing to upscaling innovations in transitions: The case of electric vehicles. Environ. Innov. Soc. Transitions 31, 96–109. https://doi.org/10.1016/j.eist.2019.01.002

Mennicken, S., Huang, E.M., 2012. Hacking the Natural Habitat: An In-the-Wild Study of Smart Homes, Their Development, and the People Who Live in Them, in: Kay, J., Lukowicz, P., Tokuda, H., Olivier, P., Krüger, A. (Eds.), Pervasive Computing. 10th International Conference, Pervasice 2012, Newcastle, UK, June 2012 Proceedings. Springer, Newcastle, UK, pp. 148–1. https://doi.org/10.1007/978-3-642-31205-2_22

Mignon, I., Kanda, W., 2018. A typology of intermediary organizations and their impact on sustainability transition policies. Environ. Innov. Soc. Transitions 29, 100–113. https://doi.org/10.1016/j.eist.2018.07.001

Mintel, 2018. UK The Connected Home Market Report. London, UK.

Moore, G.A., 2014. Crossing the Chasm, 3rd ed. Harper Business.

Muller, E., Peres, R., 2019. The effect of social networks structure on innovation performance : A review and directions for research. Int. J. Res. Mark. 36, 3–19. https://doi.org/10.1016/j.ijresmar.2018.05.003

Navigant Research Group, 2012. In-home displays, networked hem systems, standalone HEM systems, web portals, and paper bill HEM reports.

Nejat, P., Jomehzadeh, F., Mahdi, M., Gohari, M., 2015. A global review of energy consumption , CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries). Renew. Sustain. Energy Rev. 43, 843–862. https://doi.org/10.1016/j.rser.2014.11.066

OECD, 2019. Going Digital: Shaping Policies, Improving Lives, OECD Publishing. Paris, France. https://doi.org/10.1787/9789264312012-en

OECD, 2018. Consumer Policy and the Smart Home, OECD Digital Economy Papers.

Owen, A., Mitchell, G., 2015. Outside influence - Some effects of retrofit installers and advisors on energy behaviours in households. Indoor Built Environ. 24, 925–936.

Palm, A., 2017. Peer effects in residential solar photovoltaics adoption—A mixed methods study of Swedish users. Energy Res. Soc. Sci. 26, 1–10. https://doi.org/10.1016/j.erss.2017.01.008

Park, E., Kim, S., Kim, Y., Kwon, S.J., 2018. Smart home services as the next mainstream of the ICT industry : determinants of the adoption of smart home services. Univers. Access Inf. Soc. 17, 175–190. https://doi.org/10.1007/s10209-017-0533-0

Parry, M.E., Kawakami, T., Kishiya, K., 2012. The Effect of Personal and VirtualWord-of-Mouth on Technology Acceptance. J. Prod. Innov. Manag. 29, 952–966. https://doi.org/10.1111/j.1540-5885.2012.00972.x

Peres, R., 2014. The impact of network characteristics on the diffusion of innovations. Phys. A Stat. Mech. its Appl. 402, 330–343. https://doi.org/10.1016/j.physa.2014.02.003

Pettifor, H., Wilson, C., Chryssochoidis, G., 2015. The appeal of the green deal: empirical evidence for the influence of energy efficiency policy on renovating homeowners. Energy Policy 79, 161–176.

Podkalicka, A., 2019. Actor, intermediary, and context: media in home renovation and consumption practice. Commun. Res. Pract. 5, 210–225. https://doi.org/10.1080/22041451.2018.1507326

Raj, K.B., 2018. Smart Grid Technology for Smart Homes Risks and Benefits, in: ICRTEMMS Conference Proceedings. pp. 634–640.

Richmond, V.P., 1977. The relationship between opinion leadership and information acquisition. Hum. Commun. Res. 4, 38–43.

Rogers, E.M., 2003. Diffusion of Innovations, 5th ed. Free Press.

Rogers, E.M., Medina, U.E., Rivera, M.A., Wiley, C.J., 2005. Complex adaptive systems and the diffusion of innovations. Innov. J. Public Sect. Innov. J. 10, 1–25.

Russell-Rose, T., Tate, T., 2013. Chapter 2 - Information Seeking, in: Russell-Rose, T., Tate, T.B.T.-D. the S.E. (Eds.), Designing the Search Experience. The Information Architecture of Discovery. Morgan Kaufmann, pp. 23–45. https://doi.org/https://doi.org/10.1016/B978-0-12-396981-1.00002-1

Sanguinetti, A., Karlin, B., Ford, R., Salmon, K., Dombrovski, K., 2018. What's energy management got to do with it? Exploring the role of energy management in the smart home adoption process. Energy Effic.

Schill, M., Godefroit-winkel, D., Fall, M., Barbarossa, C., 2019. Consumers ' intentions to purchase smart home objects : Do environmental issues matter ? Ecol. Econ. 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. Technol. Forecast. Soc. Chang. 134, 246–253. https://doi.org/10.1016/j.techfore.2018.06.029

Söderberg, M.W., Wormbs, N., 2019. Grounded: Beyond flygskam.

Southwell, B.G., Murphy, J., 2014. Weatherization behavior and social context: The influences of factual knowledge and social interaction. Energy Res. Soc. Sci. 2, 59–65. https://doi.org/10.1016/j.erss.2014.03.019

Sriwannawit, P., Sandström, U., 2014. Large-scale bibliometric review of diffusion research. Scientometrics 102, 1615–1645. https://doi.org/10.1007/s11192-014-1448-7

Stark, T.H., Krosnick, J.A., 2017. GENSI: A new graphical tool to collect ego-centered network data. Soc. Networks 48, 36–45. https://doi.org/10.1016/j.socnet.2016.07.007

Statista, 2019. Smart home - Statistics & Facts [WWW Document]. URL https://www.statista.com/topics/2430/smart-homes/ (accessed 2.10.20).

Stern, B.B., Gould, S.J., 1988. The consumer as financial opinion leader. J. Retail Bank. 10, 43–52.

Szmigin, I., Piacentini, M., 2015. Consumer Behaviour. Oxford University Press, UK.

The Harris Poll, 2015. Consumers beginning to embrace smart home technology – even if they don't know it yet. [WWW Document]. URL http://www.theharrispoll.com/business/Consumers-Embrace-Smart-Home-Technology.html (accessed 2.12.20).

UKERC, 2019. Disrupting the UK energy system : causes , impacts and policy implications 40.

Valente, T.W., 2012. Network interventions. Science (80-.). 336, 49–53. https://doi.org/10.1126/science.1217330

Valente, T.W., 2010. Diffusion of Innovations, in: Social Networks and Health. Models, Methods, and Applications. Oxford University Press, Inc., New York, pp. 172–194.

Valente, T.W., 1995. Network models of the diffusion of innovations. Hampton Press, Cresskill NJ.

Wang, Y., 2017. Review for Identifying Online Opinion Leaders. Int. J. Econ. Manag. Eng. 11, 2519–2523.

Watson, K.J., 2015. Understanding the role of building management in the low-energy performance of passive sustainable design: practices of natural ventilation in a UK office building. Indoor Built Environ. 24, 999–1009.

Webster, J. G. (2014). The marketplace of attention: How audiences take shape in a digital age. Cambridge: MIT Press.

Weeks, B.E., Ardèvol-Abreu, A., Gil de Zúñiga, H., 2015. Online Influence? Social Media Use, Opinion Leadership, and Political Persuasion. Int. J. Public Opin. Res. 29, 214–239.

https://doi.org/10.1093/ijpor/edv050

Whittle, C., Jones, C.R., While, A., 2020. Empowering householders : Identifying predictors of intentions to use a home energy management system in the United Kingdom. Energy Policy 139, 111343. https://doi.org/10.1016/j.enpol.2020.111343

Wilson, C., Hargreaves, T., Hauxwell-baldwin, R., 2017. Benefits and risks of smart home technologies 103, 72–83. https://doi.org/10.1016/j.enpol.2016.12.047

Wilson, C., Hargreaves, T., Hauxwell-baldwin, R., 2015. Smart homes and their users : a systematic analysis and key challenges 463–476. https://doi.org/10.1007/s00779-014-0813-0

Wolske, K.S., Gillingham, K.T., Schultz, P.W., 2020. Peer influence on household energy behaviours. Nat. Energy. https://doi.org/10.1038/s41560-019-0541-9

Yamamoto, Y., 2015. Opinion leadership and willingness to pay for residential photovoltaic systems. Energy Policy 83, 185–192. https://doi.org/10.1016/j.enpol.2015.04.014

Yang, H., Lee, W., Lee, H., 2018. IoT Smart Home Adoption : The Importance of Proper Level Automation. J. Sensors 11. https://doi.org/https://doi.org/10.1155/2018/6464036

YouGov, 2018. The dawn of the connected home.

Young, M., 2018. Smart homes: digital assistants, home automation and the internet of things.