Drivers and Barriers to the Adoption of Smart Home Energy Management Systems – Users' Perspective

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Full research paper

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Abstract

Smart home energy management system (SHEMS) is a technology, through which households can decrease and manage energy consumption and avoid demand peaks. For a significant sustainable impact, SHEMS should be adopted on a large scale. Based on semi-structured interviews with three user groups (new, prospective and experienced users) from 28 households we identify drivers and barriers to the adoption of SHEMS. The key drivers to adopt SHEMS are saving energy for economic and environmental reasons, increased comfort of living, safety and curiosity. Yet, there is a lack of knowledge on SHEMS and how it relates to the larger energy system and use of renewable energy. Price of SHEMS and estimated low ROI, too complicated systems, and retrofitting problems also slow down the adoption. The results inform Information Systems research on sustainable and smart home technologies, including implications for the design of future home energy management technologies and policy planning.

Keywords smart home energy management systems, drivers and barriers, households, technology adoption

1 Introduction

Energy consumption produces about 73% of greenhouse gases (GHG), of which generation of heat and electricity is responsible for most emissions, about 30% of total GHG (IEA, 2019). Therefore, mitigating the climate change requires changes in energy production and use, including residential sector. Households are expected to be active participants in energy systems (European Commission, 2015). Yet, most households lack the means to manage their energy consumption in a sophisticated way (Buchanan, Banks, Preston & Russo, 2016). Users find it hard to see how their daily tasks and routines influence the broader energy system (Sugarman & Lank, 2015), and to make a concrete connection between their daily activities and energy consumption (Neustaedter, Bartram & Mah, 2013). In the coming years households will face guidelines for increasing energy efficiency and conservation, and demand response in homes (European Union, 2018). Home energy technologies such as smart home energy management systems (SHEMS) help users to monitor and optimize their energy use offering the users economic and environmental benefits. Despite the benefits it provides, the adoption of SHEMS is still low (Delta-EE, 2020).

SHEMS are technologies used in homes to control, monitor and automatize energy-intensive processes, mainly heating, but also e.g., ventilation and electric vehicle (EV) charging. Increasingly home electricity production (e.g., solar panels) and storage (e.g., EV battery) are integrated into the systems (Zhou et al., 2016). SHEMS reduces energy consumption, increases flexibility in energy demand and informs the user about energy consumption, thus fostering energy behaviour change (Tuomela, Iivari & Svento, 2021). SHEMS may significantly reduce households' peak demand and consequently the number of power plants for covering the peak load (e.g., Ford et al., 2014). Yet, there are also critical views on the energy saving potential and sustainability benefits of SHEMS (Sovacool & Furszyfer Del Rio, 2020). Despite the potential of SHEMS, its actualized value to households, utilities and to the environment relies on the extent SHEMS are adopted and used in homes. Hence, it is necessary to understand what kinds of drivers and barriers influence the adoption of SHEMS and the current SHEMS users.

For the lack of actual users, current knowledge of the drivers and barriers of SHEMS adoption is largely based on data of potential or new users, or other stakeholders than users. This research answers to the call for studies of real users of SHEMS, with direct experience of the technology (Sovacool & Furszyfer Del Rio, 2020). This paper builds on an empirical investigation of factors influencing SHEMS adoption. The drivers and barriers for SHEMS adoption were examined applying semi-structured interviews in 28 households representing three user groups: new, experienced, and prospective SHEMS users. The research questions of this paper are: 1) What are the core drivers of home energy management systems adoption for new, experienced, and prospective users? 2) What are the core barriers of home energy management systems adoption for these user groups? The contribution thus comes from discussions with the real users in the real context of use, including often hard-to-reach groups of non-users (prospective users). Furthermore, the paper adds to the current understanding through an overview of how the users perceive the role of SHEMS in the energy transition towards clean energy. The results indicate the users of SHEMS are a heterogeneous group with diverse needs and factors affecting the adoption of SHEMS. Also, there is a need for increased awareness on home energy technologies, and on the impact on demand-side in the whole energy system.

2 The Adoption of SHEMS

2.1 Technology Adoption

The most widely used models and theories of the process and factors in technology adoption are technology acceptance models TAM1-3 (e.g., Davis, 1989; Venkatesh & Davis, 2000; Venkatesh & Bala, 2008; Brown, 2008) and the unified theory of acceptance and use of technology (UTAUT) (Venkatesh et al., 2003). Though this research builds upon the TAM model's conceptual framework, it is too limited to address diverse user groups in different phases of adoption and use. Therefore, we derive inspiration also from the Science and Technology Studies (STS). In STS the social shaping of technology approach has been applied in research on technology design, adoption and use (Rohracher, 2003). Following this approach, we regard the drivers and barriers to the adoption of SHEMS as socio-technical factors which shape technology in technology lifecycle from innovation and design to use and implementation (Mackay & Gillespie, 1992), aiming to develop a broader, more socially grounded understanding of users and their needs (Rose, 2001). Demographic studies about technology adoption show tech-savvy people are less resistant to adopt new technologies (Ram & Jung, 1991), and younger and more educated are early adopters of home energy technologies for environmental reasons (Mills & Schleich, 2012). Also, people with stronger level of affiliation with nature are more willing to adopt new energy technologies

(Chen & Sintov, 2016). Nevertheless, demographic characteristics or intention to adopt explain little about the context and motives for adoption. Adoption of new technologies involves a lot of symbolic, practical and cognitive work beyond the initial purchasing decision (Schot, Kanger & Verbong, 2016). We wanted to understand diverse aspects of the adoption of SHEMS in depth from the user's point of view, in the context of SHEMS use, i.e., in homes. Furthermore, we wanted to explore the users' perception of SHEMS as a technology for supporting the use of clean energy.

2.2 Smart home energy management system

SHEMS consists of a user interface for the cloud server of the SHEMS provider, devices such as sensors, smart thermostats, EV charger, an occupancy sensor and a drop alarm. The system can be integrated with hot water boiler, domestic energy microgeneration, e.g., solar panels, and energy storage(s). In the future SHEMS may include or be connected to the Internet of Things for controlling the energy consumption of home appliances. SHEMS provides users with a control application, through which users can monitor and control energy use in real-time, also remotely. Together with user-centred ad hoc control smart control features of SHEMS are used in scheduling and automatization of energy use for energy conservation and to match to predicted energy supply (Ford et al., 2014). Smart control is usually primarily based on users' settings, weather and energy price data, but may also be operated from the grid. Currently, the main objective of SHEMS is to reduce the energy consumption of the most energy intensive processes, typically heating and cooling, and to optimize the energy flows in home. SHEMS may reduce the consumption of energy up to 20-30 % (Connected Devices Alliance, 2018; Tuomela, Iivari & Svento, 2020; Karlin et al., 2015). The connectivity SHEMS provides between the home and the utility can be used for balancing the grid, i.e., for demand flexibility. Energy use in residents may be reduced, increased, or shifted according to the supply of energy. More demand flexibility is required as the production relies increasingly on variable and mostly uncontrollable RES leading to more variable and unpredictable energy supply with intermittency uncertainties. Also, reserve power plants which are used in the moments of demand peaks, are often fossil fuel -based and therefore will be abolished. Usually demand flexibility through SHEMS shifts consumption to hours when energy price and/or energy generation emissions are the lowest. This results in lower GHG emissions in the residential sector due to homes' contribution to reducing marginal demand and, thus, decreasing the use of more polluting but more flexible power generation technologies such as gas power plants (Walzberg et al., 2020).

2.3 Research on the Adoption of SHEMS

Research on SHEMS has largely been conducted under the umbrella of smart home research and adoption of smart home technologies (e.g., (Balta-Ozkan, Amerighi & Boteler, 2014; Hargreaves & Wilson, 2017; Wilson, Hargreaves & Hauxwell-Baldwin, 2015; Dütschke & Fichtner, 2012; Lewis, 2011). Like researchers, also end-users see energy management as a key function of smart homes (Hargreaves & Wilson, 2017, p. 41). Though smart home research has predominantly focused on technical characteristics of smart homes (Petkov et al., 2011), during the last few years, more studies have been conducted specifically on the adoption of SHEMS (e.g., (Connected Devices Alliance, 2018; Werff & Steg, 2016)). Within the Human Computer Interaction (HCI) field there are studies on SHEMS interfaces and design (e.g., (Schwartz et al., 2013; Peacock et al., 2017; Zhao, Zhang & Crabtree, 2016; Alao, Joshua & Akinsola, 2019; Castelli et al., 2017; Alan et al, 2016)) and SHEMS users and user experience (e.g., Rodden et al., 2013; Tuomela, Iivari & Svento, 2019), but little on the adoption factors among SHEMS users in different phases of adoption.

The studies on smart homes and SHEMS indicate that the most obvious and the most common driver for the adoption of SHEMS is saving energy (Karlin et al., 2015; Hargreaves & Wilson, 2017; Balta-Ozkan et al., 2013). Users want to save energy because they expect the costs go down, but also for environmental reasons (Karlin et al., 2015), though this usually comes second to economic gains (Balta-Ozkan, Amerighi & Boteler, 2014). Yet, economic and environmental drivers intertwine closely together in the adoption of SHEMS, because saving energy is assumed to lead both to decreased spending in energy costs and to beneficial impact on the environment (Sovacool & Furszyfer Del Rio, 2020; Petkov et al., 2011). Besides, many users expect SHEMS to provide more transparent information on energy consumption and costs for understanding in detail how energy is consumed (Karlin et al., 2015; Balta-Ozkan, Amerighi & Boteler, 2014). Other drivers for SHEMS adoption are ease of control of energy use (Karlin et al., 2015), increased comfort (ibid.; Sovacool & Furszyfer Del Rio, 2020) and security in the home (Hargreaves & Wilson, 2017, p. 51). Also, the 'cool' effect (novelty and being more tech-savvy) is a driver for some adopters of SHEMS (Karlin et al., 2015).

As the slow adoption of smart home technologies implies, there are several barriers for the adoption of SHEMS. Often it is considered too expensive, retrofitting a house costly and complicated, and suitable only for homeowners with a large house and no plans to move for many years, (Balta-Ozkan, Amerighi

& Boteler, 2014; Balta-Ozkan et al., 2013; Bjelica, 2018). Energy efficiency actions, such as adopting a SHEMS, require investments, and householders hesitate to replace current functional systems with new ones. In addition to feeling cost-constrained and being thrifty, many householders are unsure what energy efficiency actions to take and how, and don't have time to study the options and take into use new measures (Paetz, Dütschke & Fichtner, 2012). Privacy issues concerning the data worries users of smart homes (Paetz, Dütschke & Fichtner, 2012; Balta-Ozkan et al., 2013). Trust, or lack of it, in utilities, SHEMS providers, or even in the government, hampers the adoption of SHEMS (Balta-Ozkan, Amerighi & Boteler, 2014; Paetz, Dütschke & Fichtner, 2012; Balta-Ozkan et al., 2013). The idea of increasing demand flexibility with SHEMS may arouse questions of giving up high levels of flexibility and adapting everyday routines to fit with electricity tariffs (Paetz, Dütschke & Fichtner, 2012), (Ruokamo et al., 2019). Some users fear for being tied to a smart contract, and risks of volatile prices (Balta-Ozkan, Amerighi & Boteler, 2014). Some households consider current systems too sophisticated, complicated and consequently too expensive (Paetz, Dütschke & Fichtner, 2012). They would prefer to manage their energy use with simpler technologies (i.e. HEMS, or smart thermostats rather than SHEMS).

3 Methodology

This study is a part of a local project which aimed at increasing households' energy efficiency and conservation in a small town in Northern Finland. Semi-structured interviews were carried out in Autumn 2018. Altogether 28 households were interviewed, of which 11 were new adopters of SHEMS, 9 were prospective users and 8 experienced users. Experienced users had used SHEMS for 2-4 years, and they told about the thoughts they had before adopting SHEMS, as they remembered. New users had just finished reflecting on the drivers and barriers for the adoption and decided to adopt a SHEMS. The prospective users had also reflected on their motives and doubts for the adoption just before the interviews but had decided to decline the adoption at that point. New and prospective users had participated in an information event about the project and SHEMS, and left their contact information for the project coordinator, or they contacted the project coordinator later for asking about SHEMS and the project. In the open event the project and two SHEMS were presented, and the public could ask questions from a researcher, SHEMS providers and the project manager. The contacts of experienced users were received from the two SHEMS providers selected for the project. Three experienced users were in the capital area, all other interviews were conducted in the Northern Finland.

The two SHEMS were selected in the project by the cheapest prices for an example house, and the new and prospective users got familiar with both systems and adopted either of them. The selected SHEMS providers Optiwatti and Cleworks are small technology companies which have designed, produced and distributed SHEMS for around 10 years. The project supported the acquisitions of SHEMS with 50% of the price of the system. The main function of the systems is to automate and optimize home heating by adjusting the home temperatures based on the pre-set settings, room temperatures and humidity, the weather forecast and the electricity prices. Hot water boiler and air heat pump can be integrated into the systems. The SHEMS aim to provide users with reduced energy consumption by lowering the temperatures in the user defined times and spaces, and on the other hand with reduced energy costs by targeting the load onto cheaper off-peak hours. Users can modify and create profiles for temperature settings, set electricity contract type and price(s) and monitor room-specific electricity consumption for heating with a control application on a laptop, a tablet or a mobile phone. The SHEMS providers had no other role in this research than providing the contacts of experienced users for the researchers to select for interviews, scheduling the installations of the SHEMS for the new users with the research timetable and giving technical specifications of the systems for the researchers.

Participants were contacted and asked for a face-to-face interview by the researcher. The interviews were conducted in the actual or potential use context of SHEMS when it was possible. Two interviews were conducted by phone and two in the office because the interviewees preferred that to their homes. The participants gave their formal consent to participate in the study and did so voluntarily without payment. They could withdraw from the study and they were fully briefed on the study aims and objectives. No participants withdrew from the study. The interview themes were the following: Before the adoption or deciding not to adopt SHEMS: 1) Why do you want / do not want SHEMS in your home? 2) What expectations and doubts do you have? 3) Who will use it, and how? Interview themes during the adoption of SHEMS: 1) What are your first impressions of SHEMS? 2) Would you show me how you input settings into the system? Interview themes after 3-6 months of use of SHEMS, 2-4 years for experienced users: 1) Have your expectations been realized through the use of SHEMS? Have there been unexpected consequences of the use of SHEMS? 2) What are your overall experiences of SHEMS? The interviews were recorded, transcribed, and analysed applying thematic content analysis. Common themes of drivers and barriers, and of understanding of SHEMS as a clean energy technology were identified as the material was listened and read through.

4 Results

4.1 Drivers for the Adoption of SHEMS

Saving in energy bills. (11 New Users (NU), 9 Prospective Users (PU), 8 Experienced Users (EU)). All interviewed households expected SHEMS to bring savings in energy bills, though 5 new users had doubts it would bring major savings. They decided to adopt SHEMS, because besides saving money, they expected it to bring other desirable consequences as well. Prospective users thought, and many of them had calculated, that the expected savings were too low to cover the investment costs. Savings should come e.g., from automation of indoor temperatures, optimizing energy consumption times, and from better understanding and control of energy use.

Comfort of living and comfortable energy management. (11 NU, 8 PU, 8 EU). Increased level of comfort of living was rather an observed and somewhat unexpected consequence of the use of SHEMS among experienced users than an initial driver. They all said the indoor temperature was steadier and changed more smoothly with SHEMS. Comfort of living increased especially in homes with water-based underfloor heating. SHEMS learns how the house reacts to the increase and decrease of indoor and outdoor temperature, and using sensor and weather data, starts to adjust thermostats beforehand to reach the scheduled room temperatures. Therefore, the temperature change of often otherwise slowly reacting underfloor heating is now smooth, and temperatures are kept constant, or as scheduled by the users. New and prospective users did not consider increased comfort of living as a driver, most probably because of lack of knowledge of peer experiences. Instead, they emphasized expectations of more comfortable energy management. SHEMS control application can be used with a computer, a tablet, or a mobile phone, also remotely. Having one user interface for controlling the energy use of the whole house was clearly an advantage compared to going around the house for adjustments. In addition, automatization was expected to save effort of constantly thinking and changing the indoor temperatures, air conditioning, air heat pump settings or car heating. Two new users considered comfort of energy management more important than possible savings SHEMS would bring.

Feedback on energy use. (11 NU, 8 PU, 2 EU). Users wanted to monitor energy use and have more detailed understanding of the energy consumption in different parts of home, and how it changes during the day and in a year. Some new users had specific questions concerning e.g., if the insulation of a door was tight enough, or how much energy the water-boiler consumed. They hoped to spot the 'energy-eaters' in home for targeting home repairs and improvements right. Also, they expected to understand better how their behaviour in home impacted energy use through the SHEMS user interface. New users considered the monitoring feature particularly important and were eager to follow their energy consumption with the control application. Only few experienced users had continued to monitor their energy use. They returned to the control application only to change settings in the turn of a heating season.

Environmental friendliness. (10 NU, 6 PU). Nearly all new users thought energy conservation was important not only for economic, but for ecologic reasons. For two new users it was a primary driver and part of the ecological lifestyle they promoted, and for the rest though not a primary driver nevertheless a significant factor. Yet none of the interviewees were aware of the significance of reducing energy production emissions through demand flexibility enabled by SHEMS. They thought optimizing energy use and not wasting energy wherever possible was important and rational in general. Experienced users had not adopted SHEMS with ecologic impacts in mind, but when asked, 4 of them said it may be one more driver for some others, and 4 of them doubted using SHEMS has any significant impact on the environment. Also, the prospective users had divided views on the importance of environmental impact: about half of them considered environmental friendliness as an important factor. The other half did not mention it, and when asked, doubted SHEMS has any impact.

Interest in new technologies. (3 NU, 5 PU, 6 EU). The second driver after saving money for some new and prospective users, and for most experienced users was curiosity for new technologies. Two new and two prospective users told they had followed the development of home energy management systems, and some of them had planned to build one themselves. These people were ready to use their time and put effort into optimizing their home with new technologies.

Safety. (8 NU, 5 PU). Possibility to monitor home energy use, temperatures and humidity would increase the sense of safety, new users expected. Experienced users did not mention safety, possibly only few of them regularly followed the application. One new user told how their toddler had turned one heating thermostat at maximum in a room which was little used, thus it took time before they found it out. This kind of energy waste would not happen with automatic control of energy use. Also, with an extra cost the users could add a leak control feature to their SHEMS, and 5 new users wanted to order it, too.

Social influence. (2 NU, 2 PU, 7 EU). Experienced users had, except for one, adopted SHEMS after developers of SHEMS had proposed it. SHEMS to-be-providers wanted to test their systems with friends, neighbours and acquaintances before launching the systems into markets. Experienced users had had no knowledge of SHEMS before someone working on SHEMS development had told about it, and asked, if they would like to try it in their home. Only one experienced user had ordered SHEMS without knowing the developers. New and prospective users were very little influenced by other people in their adoption process, and if they were, the influencers were family members, friends or colleagues.

Integration and development. (4 NU, 3 PU, 4 EU) Users hoped active and stable maintenance and development of SHEMS in the future. Users looked forward to new SHEMS features and integration to other energy-intensive and security technologies in home, e.g., optimizing production and consumption of home solar panel energy, and EV charging point. This was also a barrier for some users, who doubted SHEMS providers financial stability and were afraid the investment would lose value, if SHEMS provider were not able to continue development and service.

Trust in public administrators. (6 NU, 4 PU) Though not an initial driver, certainly a confirming one, especially for new users was that they considered their town Ii and the project reliable actors. As the level of awareness on SHEMS was very low, their hometown's participation in the project, and financial support for the adoption of SHEMS increased not only knowledge about SHEMS, but also trust on it. The users believed SHEMS must be useful and reasonable investment if it had backing of public administrators.

4.2 Barriers for the Adoption of SHEMS

Though barriers usually mean something which prevents people from doing something, we include as barriers also doubts and uncertainties some users had related to SHEMS, even if they had adopted the system. Often, studying the reasons why prospective users do not adopt a technology can be challenging. We had a unique opportunity to contact households who had participated in an information event over SHEMS and related project. They had left their contact information, and many of them were in touch with the SHEMS providers for prices and other details. Yet they decided not to adopt SHEMS. Nine such households were interviewed on the reasons why they were interested in SHEMS, and why they finally declined the acquisition. Some households had a clear and definite reasoning for not adopting SHEMS, but mostly people had considered acquisition from many different perspectives, and the decision was a sum of many factors. These barriers reflect not only the reasons why prospective users did not acquire SHEMS, but also doubts many new users had, even though they decided to adopt a SHEMS.

Lack of knowledge. (10 NU, 7 PU) SHEMS are relatively new, and the market is not yet well-established. SHEMS are not widely diffused, and householders' awareness and knowledge are barriers to SHEMS adoption. Prospective users are not familiar with the system providers. Only one new user and two prospective users (of 17 in total) were familiar with SHEMS before the project published an ad. None of them had heard anybody telling experiences of SHEMS use.

Too low estimated return on investment. (2 NU, 8 PU). The users considered the price of the system high, despite the 50 % support from the project. Depending on the size of the house, the one-time investment cost was about €1000-2500 after the project support, and the monthly service fee about €6-10. Many prospective users had calculated the system does not bring enough savings to have a reasonable payback time. Yet, though some new users had doubts SHEMS would pay itself back, they wanted to try it. The examples of savings presented by SHEMS providers were criticized as unrealistic.

Energy-saving lifestyle and house. (3 NU, 6 PU, 1 EU). Most new and prospective users had already taken many measures for energy conservation into use and minimized electricity consumption and cost. If a house is not very big (< 150 m2) and heating electricity consumption was reduced e.g., with an air heat pump and/or wood heating, SHEMS was not thought to bring much savings in energy consumption.

Too complex technology. (4 NU, 5 PU). Prospective and new users with technical skills criticized SHEMS for being too complicated and sophisticated, when less would have worked as well. Simpler system would cost less, and those could possibly be modified by users if needed. Users did not want 'a full smart home'. They wanted to begin with a simple, reliable system for energy management, with an open interface to future integrations and add-ons.

Lack of trust. (3 NU, 6 PU). As the SHEMS and system providers are not yet established and known on the market, people do not trust them. Users told they are sceptic on the examples and saving rates SHEMS providers presented. Also, the stability of the young and unknown companies was questioned, and people doubted if they were able to maintain and develop the system in the long run.

High spot-price of electricity. (2 NU, 4 PU, 1 EU). In the time of adoption decision, the price of spot-price was very high, and the variation within a day was low. Therefore, it did not encourage to invest in a system, which promised to benefit the variation of electricity price to bring savings in electricity bills. Though it was acknowledged high prices and low within-day variation may be temporary, it was not a time people would change their fixed-price electricity contracts to more risky variable prices. Also, estimating how much could be saved by automatic load shift is difficult due to unpredictability of electricity market prices, and the flexibility capacity of the residence.

The stage of technology. (1 NU, 4 PU). Some prospective users saw current SHEMS as an early-stage technology and wanted to wait for more sophisticated systems. They believed SHEMS will be more efficient, integrated into other home technologies and economic when the market develops. They raised concerns about fast-changing technology soon becoming obsolete. They were unsure what in that case would happen with the installed technology. Updates to the software and the cloud service are included in the monthly service fee, but it is unclear what the use or retail value of possibly soon obsolete technology is.

Retrofitting problems. (4 PU). Though for most houses SHEMS was relatively effortless to install, for example in houses with water-circulating floor heating a room-specific heating control can be difficult to implement. Also, the capacity of fuses was too low in two houses. Changing fuses would have caused extra costs and required different kind of electricity contract with higher monthly payments.

4.3 SHEMS as a clean energy technology

The users clearly understand SHEMS should reduce energy consumption, and that it is strongly linked to reduced energy costs. To most new and prospective users, reducing energy use is “important in general”, for avoiding over-consumption. Yet, it was a primary driver of adoption only for few users. Surprisingly, none of the users, not even the experienced ones, had considered the impact of flattening the peak demand and shifting the demand to off-peak hours to match the increased supply of RES, and reduced use of reserve power plants and imported energy. When the researcher had explained this connection, 8 of 11 new users and 7 of 9 prospective users told it would have been a significant driver, had they known it. Still, 3 users told they do not care how the energy they use is produced. Also, all 8 experienced users emphasized benefits for the family rather than for the environment or the energy system. They had doubts if SHEMS really could have an ecologic impact. The most evident reason for not considering SHEMS as a clean energy technology was the lack of knowledge and understanding of the larger energy system and the impact SHEMS may have on it. Clearly the users of SHEMS perceive the role of this technology very differently from policy makers and the energy sector.

4.4 Experienced, new and prospective users

Research on users of energy technologies indicates first users are ‘user-producers’, who “invent, experiment and tinker with radical technologies, creating new technical and organizational solutions, articulating new user preferences, and enabling new routines to emerge” (Schot, Kanger & Verbong, 2016) or ‘lead users’, who are first adopters and experimenters of new technologies (Peacock et al., 2017). Initially we assumed experienced users would represent ‘user-producers’. However, our interviews showed that they are found in all three user groups, i.e., among experienced, new and prospective users, as were also user-consumers, taking SHEMS as a part of their daily practices and for defining their lifestyle without particular interest in new technologies. This heterogeneity of users in all phases of the adoption should be addressed in SHEMS design, marketing, and maintenance. The new and experienced users adopted SHEMS into existing homes, i.e., retrofitting (Balta-Ozkan, Amerighi & Boteler, 2014). Besides SHEMS, they had considered and adopted many other ways to conserve energy. Understandably prospective users had stronger barriers for the adoption than new or experienced users. Some barriers overdrove the drivers, for example if the retrofitting SHEMS was not possible for technical reasons.

5 Concluding discussion

We examined the drivers and barriers perceived by three user groups for the adoption of SHEMS. New users balanced between expectations and doubts and did not quite know what to expect due to the low level of knowledge of SHEMS. Experienced users could tell from experience drivers for new adopters while indicated very few barriers. Prospective users had had an intention to adopt SHEMS but had given it up usually due to multiple barriers such as SHEMS not paying itself back, distrust for SHEMS providers, or installing and using SHEMS was impossible for technical retrofitting problems. Though SHEMS may provide users with many benefits, it is not suitable for all houses. Optimal results are gained in a big house with electric heating, high energy consumption, and a spot-price electricity contract.

Adoption of SHEMS is expected to increase energy conservation and demand flexibility, resulting in reduced energy costs, better energy use and cost visibility, and ultimately energy behaviour change. **Our results partly confirm the previous findings on the drivers and barriers of the adoption of smart home technologies**, indicating that despite the strong drivers, such as saving money and energy or increased comfort and safety, there are many barriers as well. SHEMS is considered too sophisticated and consequently too costly for the needs of a small house. Awareness of SHEMS and its impacts is low, there are few peer testimonies on the use of SHEMS, and the system providers are unfamiliar to users. Users' fear of obsolescence of SHEM technologies may be valid – the lifetime may be unpredictable due to fast changes both in the energy sector and smart home technologies. Users look for continuous development, expansion and integration of SHEMS with other home technologies. All new and prospective users had some doubts and potential barriers to SHEMS adoption, whereas none of the experienced users remembered any doubts or did not mention them, possibly wanting to rationalize their decisions. Yet, they had very vague understanding of the benefits SHEMS had brought to their home. Most concrete one was increased comfort particularly in homes with slowly reacting floor heating. Only half of the experienced users regularly followed their electricity consumption and had estimated how much they had saved with SHEMS. This is in line with (Hargreaves & Wilson, 2017 s. 50) findings that early adopters have less strong perception of benefits and risks than other users.

Our study generated also novel or contradicting findings. Though there is a lack of trust on SHEMS providers, unlike in other user studies (e.g., (Balta-Ozkan et al, 2013)), our interviewees did not worry about privacy risks. Only one new user raised a question of risks of someone hacking the home system through the cloud server. Nor did the users express distrust in the utilities or other energy sector stakeholders. They may have not known that utilities could control load through SHEMS, or they trusted the utility would not do that unjustifiably or without transparency. Also, retrofitting problems were technical in our study rather than related to aesthetic and atmospheric values, as in (Karlin et al., 2015). Our results also contrast the findings on users, who considered themselves competent with home energy management technologies being the least resistant to adopt SHEMS (Mills & Schleich, 2012). Conversely, in our study the users who were the most interested and knowledgeable in energy technologies criticized the SHEMS in markets for being too complicated, too expensive, and that they could, or at least would like to build themselves a cheaper system more suitable for their needs. Also, unlike in (Hargreaves & Wilson, 2017, p. 44), the role of early adopters was not influential in the adoption decision as none of our interviewees had heard about the system from other users of SHEMS. Nevertheless, the experienced users, who were the early adopters of SHEMS, had learnt about SHEMS and had been persuaded to try the system by the developers of SHEMS.

Moreover, we showed that though from the energy system perspective SHEMS connects homes to a smart grid (e.g., (Shakeri & Amin, 2018; Siano, 2014) offering the energy system great potential for systemic sustainability through demand response (Liu et al., 2016), this seems not to be of importance for SHEMS users or they are not aware of the potential connection. Demand flexibility was a distant and abstract concept for the users, and they found it hard to make a connection between the use of SHEMS and the use of renewable energy resources. The users expected SHEMS providers to tell about the linkages between SHEMS use and larger energy system and energy transition. Users' drivers for the SHEMS adoption related to their own consumption, home and family life, not to the wider, systemic impact. The users lacked knowledge of the possibilities to increase the use of clean energy with SHEMS. Energy efficiency and conservation due to SHEMS were considered economic rather than ecologic actions. Yet, when asked, most users considered environmental consequences an important driver for adopting SHEMS. This is in line with (Maibach et al., 2010) who conclude that a sense of morality, feeling good about oneself and complying with the wishes of another person are important second-tier motivators of energy efficiency actions but they rarely are the primary drivers.

Concerning the level of knowledge about electricity markets and interest in demand response, little seems to have changed in ten years (Darby & McKenna, 2012)). Experienced users usually had spot-price electricity, but only few followed how much load had been shifted and how much they had saved. Only two of 11 new users had changed their electricity contract to spot-price, the others wanted to play safe and continued with the fixed price or two-time contract.

Our results have interesting implications for IS research on "Sustainable Future, Connectedness, and Social Good", particularly for research and design of sustainable and

smart home technologies. This study has enhanced our understanding of the drivers and barriers of the end-users of sustainable home technologies, including rarely reached experienced users as well as non-users with interest in the technology. The present findings can be useful in bridging the gap between the vision of active energy citizens and actual household energy technology adoption. We show versatility in the user groups and different adoption phases and reveal a number of factors in line with as well as beyond TAM and UTAUT affecting the adoption and non-adoption of SHEMS, indicating the value of STS approach in this context. Our findings underline the importance of trust not only in SHEMS, but also in the system providers and information sources. Also, adoption and use of SHEMS are largely social, rather than individualistic processes as presented in TAM and UTAUT models. This study offers also valuable information for designers of SHEMS, who should become aware of these drivers and barriers. The concrete implications for the designers of SHEMS user experience are undisturbedness of the system in the daily home life, visualization of system operation including demand response, scalability of system for different buildings and for different needs and designing interaction for the family instead of an individual user. Overall, the designers should acknowledge they are engaged, in their small part, in shaping our domestic lives and attempting to transform its future. Hence, they should reflect on what kind of digital and sustainable futures they are creating for us and our homes as well as for the globe, and what seems to be driving the users to integrate their creations into their everyday life and practices – or not. Based on our study we maintain that large-scale SHEMS adoption will have a key role in the energy transition and result in reduced emissions if the barriers of adoption are lowered and the drivers strengthened.

Our study has also policy and business implications. Clearly there is a gap between the visions of SHEMS as a part of the energy transition and the reality. The results of this study help to develop policy instruments and business strategies fostering the adoption of home energy technologies. In order to speed up the adoption and having full benefits for users, for the energy sector and for the environment, simpler and cheaper versions of SHEMS should be designed and promoted, and awareness of the potential of SHEMS should be increased. Especially, the sustainability aspect of SHEMS is not yet well understood by most users. Our results point to the need for explaining smart energy technologies and demand flexibility to users with "a clear and careful language", as indicated also by (Darby, 2018). The gap between the current level of knowledge of average energy users and the assumed one should be addressed by policy makers, energy companies and SHEMS providers.

A set of limitations needs to be considered. First, the current study was conducted in single family detached houses in a geographically limited area. Thus, the findings might not be representative of families living in other kinds of homes and areas. Secondly, our study comprised only two kinds of SHEMS with rather similar functionality. More variety in the home energy technologies might bring up additional drivers and barriers. Larger number of users could also be inquired through quantitative studies. Despite these limitations we believe our work acts as a valuable basis for further research.

6 References

Alan, A. T., Costanza, E., Ramchurn, S. D., Fischer, J., Rodden, T. & Jennings, N. R. 2016. "Tariff Agent: Interacting with a Future Smart Energy System at Home". *ACM Trans. Comput.-Hum. Interact* (23:4), Article 25.

Alao, O. D., Joshua, J. V., & Akinsola, J. E. 2019. "Human Computer Interaction (HCI) and Smart Home Applications". *IUP Journal of Information Technology* (15:3), pp. 7-21.

Balta-Ozkan, N., Amerighi, O. & Boteler, B. 2014. "A comparison of consumer perceptions towards smart homes in the UK, Germany and Italy". *Technology Analysis & Strategic Management* (26:10), pp. 1176-1195.

Balta-Ozkan, N. Davidson, R., Bicket, M. & Whitmarsh, L. 2013. "Social barriers to the adoption of smart homes". *Energy Policy* (63), pp. 363-374.

Bjelica, M. Z. 2018. "How much smart is too much?" *IEEE Consumer Electronics Magazine*, November 2018, pp. 23-28.

Brown, S. 2008. "Household technology adoption, use, and impacts: Past, present, and future". *Information Systems Frontiers* (10), p. 397.

Buchanan, K., Banks, N., Preston, I., & Russo, R. 2016. "The British public's perception of the UK smart metering initiative". *Energy Policy* (91), pp. 87-97.

Castelli, N., Ogonowski, C., Jakobi, T., Stein, M., Stevens, G., & Wulf, V. 2017. "What Happened in my Home?: An End-User Development Approach for Smart Home Data Visualization". *Proceedings of the 2017 CHI, Denver Colorado USA, May 2017,* pp. 853–866.

Chen, B. & Sintov, N. 2016. "Bridging the gap between sustainable technology adoption and protecting natural resources: Predicting intentions to adopt energy management technologies in California". *Energy Research & Social Science* (22), pp. 210-223.

Connected Devices Alliance. 2018. *Intelligent Efficiency: A Case Study of Barriers and Solutions - Smart Homes*. Energy Efficient End-Use Equipment Technology Collaboration Programme.

Darby, S. J. & McKenna, E. 2012. "Social implications of residential demand response in cool temperate climates". *Energy Policy* (49), pp 759-769.

Darby, S. J. 2018. "Smart technology in the home: time for more clarity". *Building Research & Information* (46:1), pp. 140-147.

Davis, F. D. 1989. "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology". *MIS Quarterly* (13:3), pp. 319-340.

Delta-EE. 2020. *Accelerating the energy transition with Home Energy Management: Why the HEM market is at a tipping point in Euro*. Delta-EE.

European Commission. 2015. *Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation*. Bryssels: EC.

European Union. 2018. *Energy Performance of Buildings Directive as amended by Directive (EU) 2018/844 (EPBD)*. EUR-Lex: https://eur-lex.europa.eu/eli/dir/2018/844/oj

Ford, R., Stephenson, J., Brown, N., & Stiehler, W. 2014. *Energy Transitions: Home Energy Management Systems (HEMS)*. Centre for Sustainability.

Goncalves Da Silva, P., Karnouskos, S., & Ilic, D. 2012. "A Survey Towards Understanding Residential Prosumers in Smart Grid Neighbourhoods". *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Berlin, October 14-17. IEEE.

Hargreaves, T. & Wilson, C. 2017. *Smart Homes and Their Users*. (Vols. Springer Briefs in Human-Computer Interaction). Springer.

IEA. 2019. *Global Energy & CO2 Status Report 2019*. https://www.iea.org/reports/global-energy-co2-status-report-2019

Karlin, B., Ford, R., Sanguinetti, A., Squiers, C., Gannon, J., Rajukumar, M., & Donnelly, K. A. 2015. *Characterization and Potential of Home Energy Management (HEM) Technology*. San Francisco, CA: Pacific Gas and Electric.

Lewis, S. 2011. "Energy in the Smart Home". In R. Harper: *The Connected Home: The Future of Domestic Life*. London: Springer-Verlag.

Liu, Y., Qiu, B., Fan, X., Zhu, H. & Han, B. 2016. "Review of Smart Home Energy Management Systems". *Energy Procedia* (104), pp. 504-508.

Mackay, H. and Gillespie, G. 1992. "Extending the social shaping of technology approach: ideology and appropriation". *Social Studies of Science* (22), pp. 685-716.

Maibach, E., Leiserowitz, Roser-Renouf, C., Akerlof, K. & Nisbet, M. 2010. "Saving energy is a value shared by all Americans: Results of a global warming audience segmentation analysis". In K. E.-M. (Ed), *Human Resources for Climate Solutions: Energy Smart Behaviors, People Centered Policies, and Public Engagement* (pp. 8-1 - 8-14). Washington, DC: American Council for an Energy-Efficient Economy.

Mills, B. & Schleich, J. (2012). "Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries". *Energy Policy* (49) pp. 616-628.

Neustaedter, C., Bartram, L., & Mah, A. 2013. "Everyday Activities and Energy Consumption: How Families Understand the Relationship". *CHI 2013: Changing perspectives*. Paris, France.

Paetz, A. D., Dütschke, E. & Fichtner, W. 2012. "Smart Homes as a Means to Sustainable Energy Consumption: A Study of Consumer Perceptions". *Journal of Consumer Policy* (35) pp. 23-41.

Peacock, A., Chaney , J., Goldbach, K., Walker, G., Tuohy, P., Santoja, S., Todoli, D. & Owens, E. 2017. “Co-designing the next generation of home energy management systems with lead-users”. *Applied Ergonomics* (60), pp. 194-206.

Ram, S., & Jung, H.-S. 1991. ““Forced” adoption of innovations in organizations: Consequences and implications”. *Journal of Product Innovation Management*, (8:3), pp. 117-126.

Rodden, T. A., Fischer, J. E., Pantidi, N., Bachour, K. & Moran, S. 2013. “At home with agents: exploring attitudes towards future smart energy infrastructures”. *CHI ’13*. ACM, New York, NY, USA, pp. 1173–1182.

Rohracher, H. 2003. “The Role of Users in the Social Shaping of Environmental Technologies”. *Innovation* (16:2), pp. 177-192.

Rose, D. A. 2001. “Reconceptualizing the user(s) of – and in – technological innovation: the case of vaccines in the United States”. In Coombs, R. et al (eds.), *Technology and the Market. Demand, Users and Innovation*, Cheltenham and Northampton, Edward Elgar, pp. 68-88.

Schot, J., Kanger, L., & Verbong, G. 2016. “The roles of users in shaping transitions to new energy systems”. *Nature Energy* (1:5), 1-7.

Shakeri, M., & Amin, N. 2018. “Transformation of Conventional Houses to Smart Homes by Adopting Demand Response Program in Smart Grid”. In M. Nayeripour, *Smart Microgrids,* London: IntechOpen. pp. 65-79.

Schwartz, T., Denef, S., Stevens, G., Ramirez, L. & Wulf, V. 2013. “Cultivating energy literacy: results from a longitudinal living lab study of a home energy management system”. *CHI ’13*. ACM, New York, NY, USA, pp. 1193–1202.

Siano, P. 2014. “Demand response and smart grids”. *Renewable and Sustainable Energy Reviews* (30), pp. 461-478.

Sovacool, B. K. and 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.

Sugarman, V., & Lank, E. 2015. “Designing Persuasive Technology to Manage Peak Electricity Demand in Ontario Homes”. *CHI 2015*, Crossings. Seoul, Korea, April 18 - 23.

Tuomela, S. Iivari, N. & Svento, R. 2020. ”Impact of home energy management system on energy consumption”. *Applied Energy* (299), 117310.

Tuomela, S., Iivari, N., & Svento, R. 2019. “User values of smart home energy management system: sensory ethnography in VSD empirical investigation”. *Proceedings of MUM ’19*. Pisa, Italy, 27-29 November. ACM.

Venkatesh, V. & Bala, H. 2008. “Technology acceptance model 3 and a research agenda on interventions”. *Decision Sciences*, (39:2), pp. 273-315.

Venkatesh, V. & Davis, F. 2000. “A theoretical extension of the technology acceptance model: four longitudinal field studies”. *Management Science*, (46:2), pp. 186-204.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. 2003. “User Acceptance of Information Technology: Toward a Unified View”. *MIS Quarterly*, (27:3), pp. 425–478.

Werff, E. v., & Steg, L. 2016. “The psychology of participation and interest in smart energy systems: Comparing the value-belief-norm theory and the value-identity-personal norm model”. *Energy Research & Social Science* (22), pp. 107-114.

Wilson, C., Hargreaves, T. & Hauxwell-Baldwin, R. 2015. “Smart homes and their users: a systematic analysis and key challenges”. *Personal and Ubiquitous Computing* (19:2), pp. 463–476

Walzberg, J., Dandres, T., Merveille, N, Cheriet, M. & Samson, R. 2020. “Should we fear the rebound effect in smart homes?” *Renewable and Sustainable Energy Reviews* (125), 109798.

Zhao, Y., Zhang, X., & Crabtree, J. 2016. “Human-computer interaction and user experience in smart home research: A critical analysis”. *Issues in Information Systems* (17:III), pp. 11-19.

Zhou, B., Li, W., Wing Chan, K., Cao, Y., Kuang, Y., Liu, X. & Wang, X. 2016. “Smart home energy management systems: Concept, configurations, and scheduling strategies”. *Renewable and Sustainable Energy Reviews* (61), pp. 30-40.

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