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Original research article

"It's never telling me that I'm good!" Household experiences of testing a smart home energy management system with a personal threshold on energy use in Sweden

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A R T I C L E I N F O

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A B S T R A C T

Although smart technologies are widely promoted as enabling flexibility in households' energy demand, they often fail to achieve substantial impact. How smart technologies are actually used and to what extent they enable changes of energy-reliant practices in everyday life therefore needs to be better understood. This paper evaluates a smart home energy management system, Ero 2.0, which was tested by households in a multi-residential building in Sweden. To our knowledge, apart from its forerunner, Ero 2.0 is the first of its kind to include a personal threshold on energy use varying with the availability of preferred energy sources. Semi-structured interviews were conducted with 15 participants, complemented by pre and post surveys, answered by 39 and 32 participants respectively. Overall, Ero 2.0 contributed to raised awareness regarding electricity and water use. To some extent, it also contributed to changes in practices, mainly through changed or reduced use of certain functions. However, it was less effective in enabling shifting practices in time. Difficulties to change practices were found to depend on: (1) lack of flexibility in everyday life, (2) limitations in size and layout of the dwelling, (3) lack of incentives and perceived impact, (4) lack of guidance and (5) lack of possibilities to control devices through the interface. The second point is an aspect that to date has received little attention in smart energy research. Design opportunities for future smart home energy management systems are discussed while acknowledging that such technologies cannot alone achieve the transition to more sustainable energy systems.

1. Introduction

It is widely acknowledged that a transition to more sustainable energy systems is essential in order to mitigate climate change. This involves integrating a higher share of renewable energy sources, such as wind and solar power, and consequently dealing with a fluctuating energy supply [1]. Smart energy systems, which include new technologies and infrastructures, have been promoted as a promising strategy for facilitating a better match between energy demand and supply and thus an important contributor to the decarbonisation of the energy sector [1,2].

With the ongoing energy crisis, "*a global focus on the demand side of the energy equation has never been more important*" [3]. In the European Union, approximately a quarter of the final energy consumption can be attributed to households [4]. To enable households to manage their energy consumption at home, there have been widespread developments of Home Energy Management Systems (HEMS), combining real-time energy feedback with smart home features. However, the effectiveness of smart technologies in supporting households to reduce and shift energy use in time has varied and their environmental benefits have thus been questioned [5,6]. It has even been suggested that smart home technologies might lead to increased energy use as a result of promoting more energy-intensive comfort expectations and lifestyle images [7–9]. Among others, Wilson and colleagues claim that "[…] *a clear user-centric vision of smart homes is currently missing from a field being overwhelmingly 'pushed' by technology developers*" ([10], p. 464). Thereby, there is a general need to increase the understanding of users of smart home technologies [9–12] in their everyday home contexts [13,14].

This paper presents the development and testing of a HEMS prototype, Ero 2.0, in a multi-residential building in Sweden during spring 2020. Ero 2.0 is a mobile application that includes a personal electricity threshold guiding households to adapt their energy use to the availability of their preferred energy sources. The study builds on a previous in-situ exploration of a former version, Ero 1.0, presented in [15]. Apart

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from Ero 1.0 and 2.0, we have not come across any other HEMS including a personal threshold on energy use varying with the availability of users' own preferences regarding energy sources. For a more holistic perspective on resource consumption, Ero 2.0 also presents water consumption data to the household. The aim of the study was to increase the understanding of how households perceive HEMS and to what extent such systems may support them in changing energy-reliant practices in everyday life.

The empirical material is analysed through a framework of social practice theory. Based on findings from the testing of Ero 2.0, the following focus areas are discussed: (1) effects on practice elements, (2) reconfigurations and time-shifting of energy-reliant practices, (3) perceived barriers to changing energy-reliant practices and (4) design opportunities for future HEMS to support flexibility in energy use for a diversity of people. The practices in focus are mainly those connected to the use of larger home appliances such as laundry and dishwashing but also the use of floor heating.

2. Background

2.1. Households' role in smart energy systems

Households play a crucial role in the future of smart energy systems; the extent to which they are willing to accept changes in their everyday practices at home will have considerable impact on the success of such systems [16]. However, smart technologies have so far often been designed with a narrow vision of the user in mind, illustrated by Strengers as the "Resource Man" [17]. This "ideal user" is someone who is "*interested in his own energy data, understands it, and wants to use it to change the way he uses energy*" ([17], p. 26). However, even for users who are considered active and interested in their energy data, engagement in energy management has been found to fade over time with little effects on energy use [18].

In generative group sessions, Renström [19] identified a diversity of roles that the participants imagined playing in future smart energy systems. Some imagined their role similar to that of "Resource Man", while others simply wanted to be told what to do without having to be active managers of their energy use. From the results, Renström [19] summarised three ways in which products, services and systems may support users in smart energy systems: (1) providing information (general or context-specific), (2) enabling different ways of controlling products and (3) changing the preconditions for energy use by introducing alternative ways of using, storing and producing energy.

Cockbill and colleagues [20] suggest that in order to support diverse roles of households, future energy services should accommodate for varying levels of interest, knowledge and engagement among users and be able to adapt to changes over time. Several other studies have highlighted challenges and conflicts that may arise due to different expectations on smart home systems, levels of technological proficiency and roles taken on by different members of the same household [9,11]. While smart technologies may improve control over the home for some household members, it may at the same time reduce the perceived control for other members [11,14,21]. This underlines the importance of understanding both users and non-users of smart home technologies and treating the household as a system in itself.

2.2. Households' flexibility in everyday practices

Theories of social practice are widely applied by researchers to understand households' resource consumption in relation to the dynamics of everyday life. From a social practice theory perspective, "*consumption occurs within and for the sake of practices*" ([22], p. 145). In other words, energy is used as a result of engaging in different everyday practices such as cooking, doing laundry or watching television.

Several definitions exist regarding how practices are formed by different categories of elements that are interconnected with each other. In the present article, we use the definition provided by Shove et al. [23], in which practices are understood as combinations of elements within three categories: *materials*, *competences* and *meanings*. Practices can be linked together with other practices, forming "*bundles and complexes*". Bundles are described as "*loose-knit patterns based on the colocation and co-existence of practices*", while complexes are explained to "*represent stickier and more integrated combinations*" ([23], p. 62).

Peaks in energy use can be understood as bundles of practices as they are a result of several (energy-reliant) practices being carried out simultaneously [24]. In a study focusing on households with children, Nicholls and Strengers suggested that such practice bundles might even turn into complexes due to daily routines being both "*practically and emotionally 'stuck together'*" during certain times of the day ([24], p. 122). Some of the "peak practices" were found to be dependent on several household members being at home and available to perform the practice together. Important meanings and competences could sometimes only be reproduced by performing these practices during peak hours and many peak practices were synchronised around daily routines, largely influenced by school and work hours as well as other outside school activities. In another study, Nyborg and Røpke [25] identified four factors influencing a household's flexibility to change practices: (1) willingness to flexibility, (2) household composition, (3) life situations and (4) household infrastructure and smart technologies.

Southerton [26] previously suggested that the performance of practices is shaped by both collective and personal "temporal rhythms". Examples of collective temporal rhythms are institutionally timed events such as school and work hours, while personal temporal rhythms are individual timing strategies. Furthermore, practices constantly compete for time and different practices require different levels of coordination or synchronization with other people and practices [26].

Several researchers have attempted to identify energy-reliant practices which are more or less flexible to time-shift. One group of domestic practices which has been highlighted as potentially more flexible than others is cleaning practices, mainly focusing on laundering and dishwashing [18,24,25,27–29]. Smale et al. [29] further suggest that practices involving lighting, heating and cooling of spaces are not suitable for active demand response but instead show potential for automation in order to create flexibility in energy demand. They further explain that practices involving cooking, eating and leisure play an important role in nurturing social bonds between household members. Although such practices particularly contribute to evening peaks in energy demand, they are generally inflexible because they often require coordination between several persons and are often centred around relaxation [29].

Friis and Christensen [27] found the practice of charging electric vehicles to be rather easily integrated into an already existing sequence of daily routines. However, they also found that time-shifting complicated the performance of some other practices by bringing additional things to do and plan, such as unloading the dishwasher and hanging laundry to dry in the morning. This was something that especially contributed to feelings of stress during already time-pressured weekday mornings.

In summary, previous research has given insight into how flexible different categories of domestic practices are. Still, what limits the flexibility in households' energy demand and how they can be better supported in changing practices need to be better understood.

2.3. Previous in-situ explorations of energy feedback and smart home systems

In a UK field trial by Hargreaves and colleagues [9], smart home technologies were found to unsettle existing roles among household members but also existing technologies in the home, which sometimes became perceived as old and in need of replacement. Smart home technologies were thus described as both "technically and socially disruptive". Furthermore, participants made little or no use of the smart home technologies to manage their energy use and learning to use them was found to be a demanding task, for which very limited support was available.

Verkade and Höffken [18] investigated Dutch households' use of an energy monitoring platform and its effects on energy use practices. Generally, the participants found it difficult to be flexible in their electricity use and the project did not result in any measurable time-shifting of energy usage. Using a practice theory perspective, Verkade and Höffken [18] suggested that even if elements to form a new practice are available, the complicated nature of energy-reliant practices may prevent users to apply new insights and change established energy use patterns.

In a Norwegian study, Skjølsvold and colleagues [30] identified four kinds of re-arrangements which were accommodated by energy feedback: knowledge re-arrangements, material re-arrangements, social re-arrangements and routine re-arrangements. However, in accordance with several other studies, their findings indicate that feedback technologies do not necessarily contribute to extensive changes in households' energy use and may instead give rise to several problems. For instance, knowledge re-arrangements may contribute to feelings of disempowerment as users realise how little impact they can make as much of the electricity use is out of their control [30].

Another study by Geelen et al. [31] explored the use of smartphone and tablet applications providing energy feedback to households in the Netherlands. Although no significant reductions in electricity and gas consumption levels were identified, the participants reported that the apps had contributed to higher awareness and some changes in energy use. Yet, the interviewed households seemed to use the apps mainly for monitoring their energy use over time rather than to lower their energy use. Thereby, to better support energy savings, Geelen and colleagues suggested that such applications should provide more concrete and actionable information in relation to each household's specific situation.

Nilsson et al. [32] investigated the use of a HEMS among Swedish households. Smart meter data revealed that the effect on energy use varied greatly, showing both reductions and increases in the households' consumption. From interview data, four different obstacles for changed behaviour were summarised: (1) not enough support for increased knowledge, (2) a lack of sense of control, (3) perceiving consumption as justifiable and reasonable, and (4) differences in attitudes among household members.

Öhrlund et al. [33] investigated Swedish households' responses to dynamic price signals and energy feedback. They found that the participants had adapted their energy use in a number of ways, such as shifting some practices to off-peak hours and spreading the use of appliances so that they were not running at the same time. However, it seemed that the feedback itself played a limited role in supporting these changes. Thus, Öhrlund et al. [33] suggested that rather than investing in energy feedback systems, it might be more effective to educate households about how to respond to price signals.

Christensen et al. [34] evaluated three smart grid interventions in Denmark, Norway and Austria from a practice theory perspective. Their findings suggest that price do play a role as an incentive to change energy-reliant practices but needs to be combined with nonfinancial factors to make such changes meaningful. They also noted a risk with providing too much information as this might disengage participants to make efforts in adapting their energy use.

In summary, although energy feedback and smart home systems have been widely researched, they have often had limited effect on households' energy use. Households' interest in such technologies has often been found to decrease over time and it generally seems difficult to become more flexible in everyday energy use. Most HEMS focus on energy consumption and few of them enable monitoring of other kinds of resource consumption, such as water. As stated previously, we have not found any other HEMS that include a personal threshold on energy use, apart from Ero 1.0 [15]. It is therefore relevant to explore how a HEMS that includes those features is perceived by users and to what extent it may support them in changing practices in everyday life.

3. Research approach and methods

3.1. Research context and development of the Ero application

Ero 1.0 [15], is an application designed to support users in planning their energy use according to a personal energy threshold, based on the availability of their preferred energy sources. It was tested by users in a Living Lab during 2018–2019.

Ero 2.0 further built on the ideas underpinning Ero 1.0 and insights from its user evaluation but was developed for a different study context: a multi-residential building with a total of 70 rental apartments located in Malmö in southern Sweden. This building was newly constructed, and the residents moved in only a couple of months before the study started. In total, 44 participants from 35 households signed up for the study before moving in. Their apartments were then prepared by installing technical equipment to enable the study.

Similar to its forerunner, Ero 2.0 included a personal electricity threshold, intended as a guide to encourage participants to shift energy-reliant practices such as laundry to times when there is higher availability of their preferred energy sources. The electricity threshold could be configured during the first login procedure and then changed at any time during the study (see Fig. 2, right). The electricity threshold was also based on the households' average electricity use. This means that those with lower electricity use got a lower electricity threshold. The formula for calculating the electricity threshold was as follows:

$$\textit{Electricity threshold} = \textit{Average momentary electricity use} \times \left(\frac{\textit{Current share of selected energy sources}}{\textit{Yearly average share of selected energy sources}}\right)^2$$

Electricity use in relation to the electricity threshold was displayed as a momentary ratio on the home screen of the app (see Fig. 1, left) and over time in the more detailed electricity screen (see Fig. 1, middle and right). Each apartment of the participating households was equipped with four smart plugs connected to the washing machine, tumble dryer, dishwasher and either a separate fridge or a combined fridge/freezer column. Some of the smaller apartments had a combined washing machine and tumble dryer and therefore only used three smart plugs in total. The smart plugs enabled monitoring electricity use of the appliances practically in real time, with data being updated approximately every 5 min. Floor heating in the bathroom could be turned on and off via the home screen of Ero 2.0 in all participants' apartments except four, in which the floor heating and lights were connected to the same circuit and could not be controlled separately.

Furthermore, the app enabled monitoring of hot and cold-water consumption. This was displayed in relation to a "daily budget" based on the households' average consumption, both as a ratio on the home screen and in a more detailed screen showing water use over time (see Fig. 2, left). Water consumption data was updated every 24 h. Finally, a "statistics" screen presented approximate numbers of how much of the Swedish energy production that came from different energy sources, both momentarily and over time (see Fig. 2, middle). This data was

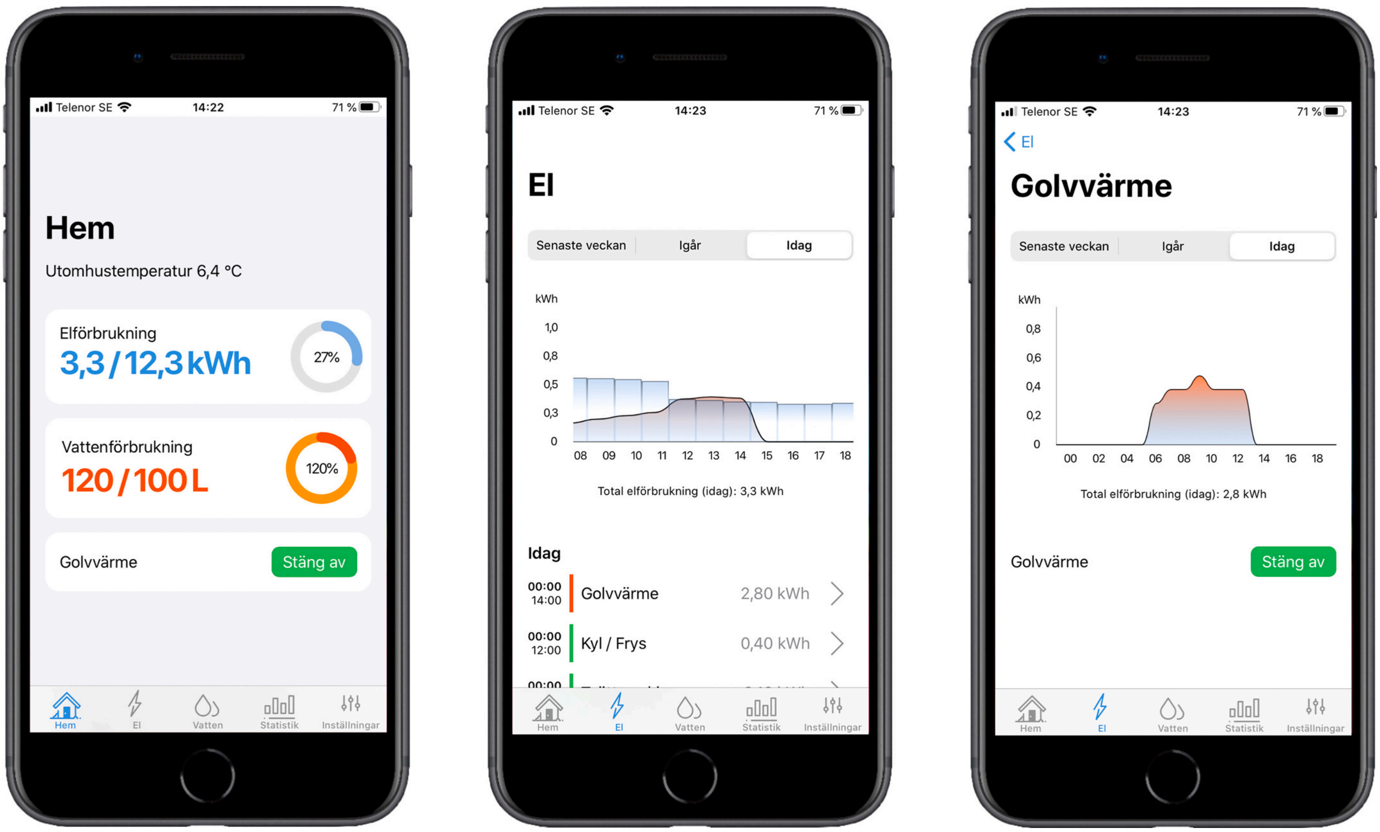

Fig. 1. Ero 2.0 in light mode. Home screen showing momentary electricity consumption and daily water use with possibility to control floor heating (left), electricity screen showing total consumption for appliances connected to smart plugs and floor heating in relation to the personal electricity threshold (middle) and electricity screen with appliance specific consumption (right).

retrieved from ENTSO-E.[1]

Ero 2.0 was designed for iOS devices only. The 14 participants who did not own an iPhone or iPad borrowed one during the study. Participants were notified: (1) when they passed their electricity threshold, (2) when the floor heating had been turned on for a longer period, (3) as a weekly report on electricity consumption compared to last week and (4) as a weekly report on water consumption compared to last week.

Some technical issues appeared in the beginning of the study that needed to be taken care of, for instance, data losses during some periods for some participants and notifications that had not been sent. For simplicity, "Ero 2.0" will hereafter be referred to as "Ero".

3.2. Data collection and participants

Fig. 3 shows a timeline of the study activities with the number of participants in parentheses. An introduction event was held in February 2020 where the research team presented the study to the participants and guided them through the different functions of Ero. Those who could not attend the event were sent information by mail and were offered a digital introduction. All participants were asked to answer a pre survey to collect demographic data, current energy and water consumption habits and opinions regarding energy use at home.

After about one month of testing Ero, the participants were asked to take part in a mid-study interview to see how the testing was experienced so far. The testing then continued until May, when a post survey was distributed to the participants. This survey had the main purpose of evaluating the app and its potential impact on activities using energy and water. In both surveys, the participants were asked to respond to several statements using Likert scales. The participants could then sign up for a final interview to provide deeper insight into how Ero was used and perceived and any changes in everyday practices that it might have contributed to.

Table 1 shows an overview of the participants' demographic data and the study activities in which they took part. The study included participants from a variety of ages but unfortunately, no residents in the 65+ age groups were recruited and only few of the participating households had children. Thus, the possibilities to generalise findings from this study are limited and the paper should mainly be seen as case study [35].

Due to the COVID-19 pandemic, all interviews were held online via Zoom. Audio was recorded with permission from the participants. Gift cards to a streaming service were given to all post survey respondents and an additional one to the interviewees.

3.3. Analysis

The interviews were transcribed and imported to NVivo. The two first authors coded half of the interviews each, using an approach guided by Gioia et al. [36]. Then, the first author combined the two files into one, reviewed the categories, merged similar ones, added some codes and adjusted the structure to include all categories in a comprehensive way. Interesting and illustrative quotes were picked out and, if originally in Swedish, translated to English by the first author.

4. Findings

This section presents insights into the participants' comments on setting up and using Ero in everyday life, followed by perceived effects from the trial on electricity and water-reliant practices. All quotes

[1] https://www.entsoe.eu.

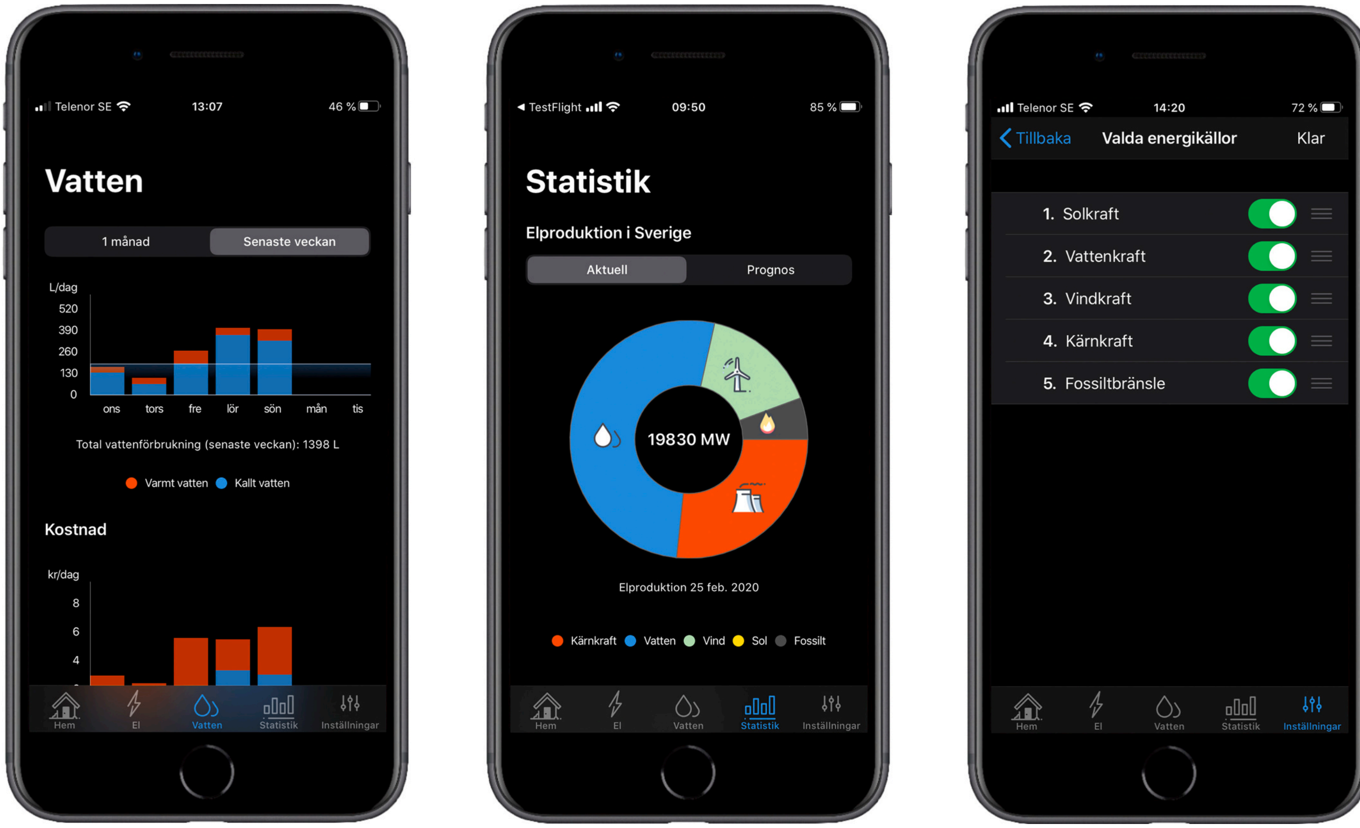

Fig. 2. Ero 2.0 in dark mode. Water screen showing hot and cold-water consumption and cost (left), statistics screen with Swedish electricity production data (middle) and personal electricity threshold settings (right).

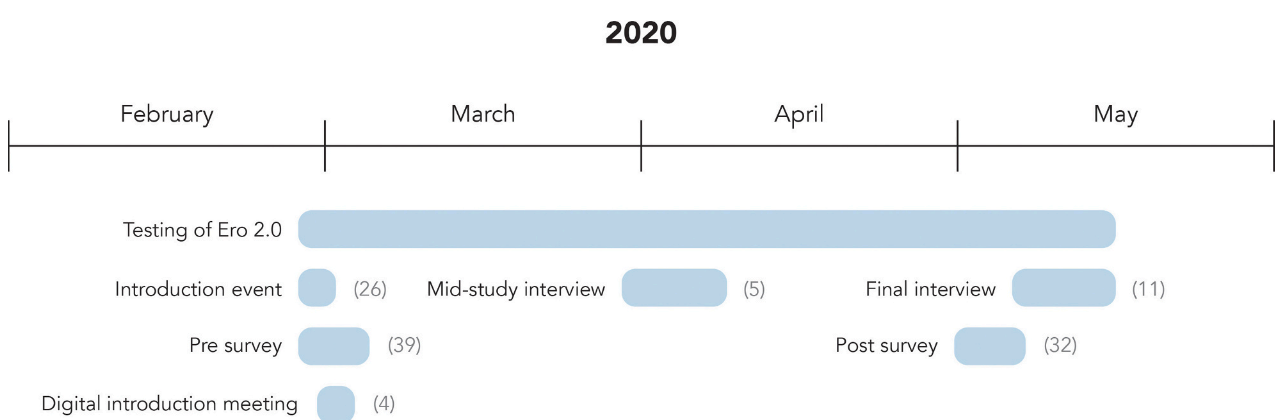

Fig. 3. Timeline of study activities and number of participants (in parentheses).

included in the text originate from the interviews.

We recognise that the use of a specific appliance is not a practice in itself but view such activities as part of wider practices. For instance, using the washing machine and tumble dryer are part of the practice of doing laundry. Similarly, using the floor heating is part in the practice of heating the home. Changing the use of a specific appliance also rearranges the elements of the practice which it is part of.

4.1. Setting up the electricity threshold

Overall, most of the interviewees seemed to appreciate the possibility to set their own electricity threshold and basing it on personal preferences for energy sources. However, several interviewees experienced that they lacked the knowledge needed to make a well-informed selection. Also, one interviewee explained that: "[…] *even when I added nuclear power and those things, I kind of thought that it didn't make such a big difference on the electricity threshold* […]" (28-M). Another interviewee wanted the possibility to compare the differences between energy sources from a local and global perspective:

> […] *I guess that here in Skåne, there is probably more solar power than in Stockholm* […] *So, I would have liked to understand a little more about what these different sources mean in my local context then maybe and in the global for sustainability*
>
> (12-F)

Overall, the electricity threshold caused a lot of confusion. A common misinterpretation was that the selection of energy sources in Ero meant that only the selected sources would actually be used. However,

Table 1
Information about study participants. The participant ID specify gender (F for female and M for male).

Household	Participant ID	Age	Adults	Children	Dwelling size (m^2)	Rooms	Pre survey	Mid-study interview	Post survey	Final interview
1	1-F	25–34	1	–	40–49	2	Yes	–	Yes	–
2	2-F	35–44	2	2	90–99	4	Yes	–	Yes	–
	2-M	45–54					Yes	–	–	–
3	3-M	18–24	1	–	60–69	2	Yes	–	–	–
4	4-M	25–34	2	–	40–49	2	Yes	Yes	–	–
	4-F	25–34					Yes	Yes	Yes	–
5	5-F	45–54	2	–	60–69	3	Yes	–	–	–
6	6-M	45–54	2	–	80–89	4	Yes	–	Yes	Yes
7	7-F	25–34	2	–	40–49	2	Yes	–	Yes	–
8	8-F	25–34	2	–	80–89	4	Yes	–	Yes	–
9	9-F	25–34	2	–	60–69	2	Yes	–	Yes	–
	9-M	25–34					Yes	–	Yes	–
10	10-F	18–24	1	–	40–49	1	Yes	–	Yes	Yes
11	11-M	55–64	2	–	90–99	4	Yes	–	Yes	–
12	12-F	25–34	1	–	30–39	1	Yes	–	Yes	Yes
13	13-F	55–64	1	–	90–99	4	Yes	–	–	–
14	14-F	35–44	1	–	40–49	2	Yes	–	Yes	–
15	15-M	35–44	2	1	90–99	4	Yes	Yes	Yes	Yes
	15-F	35–44					Yes	–	Yes	–
16	16-M	45–54	1	–	40–49	2	Yes	–	–	–
17	17-F	45–54	1	1	70–79	3	Yes	–	Yes	–
18	18-F	45–54	2	–	90–99	4	Yes	–	–	–
	18-M	45–54					Yes	–	–	–
19	19-M	35–44	1	–	50–59	2	Yes	Yes	Yes	–
20	20-M	25–34	1	–	30–39	1	Yes	–	Yes	–
21	21-M	25–34	2	–	70–79	3	Yes	–	Yes	–
	21-F	25–34					Yes	–	Yes	–
22	22-M	25–34	1	–	90–99	4	Yes	–	Yes	Yes
23	23-M	55–64	2	–	80–89	4	Yes	Yes	Yes	–
	23-F	55–64					Yes	–	Yes	–
24	24-M	25–34	1	–	40–49	2	Yes	–	Yes	–
25	25-M	35–44	1	–	50–59	2	Yes	–	Yes	–
26	26-M	45–54	2	1	70–79	3	Yes	–	Yes	Yes
27	27-M	25–34	1	–	30–39	1	Yes	–	Yes	Yes
28	28-M	25–34	1	–	30–39	1	Yes	–	Yes	Yes
29	29-F	18–24	2	–	50–59	2	Yes	–	Yes	Yes
	29-M	25–34					Yes	–	Yes	Yes
30	30-F	25–34	1	–	40–49	2	Yes	–	Yes	–
31	31-M	55–64	1	–	60–69	2	Yes	–	Yes	Yes
32	32-M	–	–	–	50–59	2	–	–	Yes	–

the electricity threshold settings in Ero only communicated when the availability of the selected energy sources was high or low based on approximated data on the electricity production in Sweden.

It was also generally not understood that the electricity threshold was based on each household's own average electricity use. When they crossed the threshold, many therefore misinterpreted this as if they were using unusually high levels of electricity compared to other households. Additionally, due to technical issues some of the participants initially got incorrect numbers on their consumption levels, which naturally caused confusion as well. In summary, Ero communicated unclear meanings of the electricity threshold and was not successful in supporting the participants to develop the competences needed to use it effectively.

4.2. Using Ero in everyday life

A majority of the participants reported that they had used Ero only a few times during the study. Some interviewees stated that checking Ero was mainly connected to receiving notifications. A few checked it mainly during the evenings and some used Ero occasionally to track their consumption, for instance after doing the laundry.

Many of the interviewees explained that their use of Ero decreased somewhat during the study. Some reasons for not using it much were technical problems, lack of motivation, having Ero on a borrowed iPhone or iPad instead of one's own phone or simply because of not being home much. One interviewee found little motivation to use Ero because: "[…] *I'm a single household and there's a limit to how much electricity I can save and how much electricity I can actually use*" (31-M).

One couple discussed that they liked the idea of having Ero but had talked about it more than they used it. One of them explained: "[…] *that is exactly why I have a problem with the app, because it's another thing that takes my attention*" (4-F).

Previous experiences of smart home technologies seemed to influence the participants' interest in using the app, both positively and negatively. Some of the participants who had experimented on their own with smart home technologies felt somewhat limited by the Ero interface and wanted to extract the data to combine it with other systems. One of them explained: "*Ero is my fifth like smart home app that I use* […] *So together all those, there's too many apps.*" (15-M).

4.3. Changes in competences, materials and meanings

Ero both introduced new and strengthened some existing competences through feedback on energy and water consumption, and energy production statistics. As shown in Fig. 4, many of the respondents to the post survey experienced getting a better understanding of their electricity use, both generally and specifically for different devices, and also regarding their water use.

These survey results were confirmed in the interviews. The possibility to see the electricity consumption specifically for individual devices or appliances seemed to be appreciated and contributed to a greater understanding for what consumes energy at home. Several of the devices connected to smart plugs were mentioned to consume more electricity than expected, including the floor heating, tumble dryer and fridge. One interviewee explained: "*I noticed that the fridge used a lot of electricity – I wasn't aware of that. And* […] *I became much more aware of*

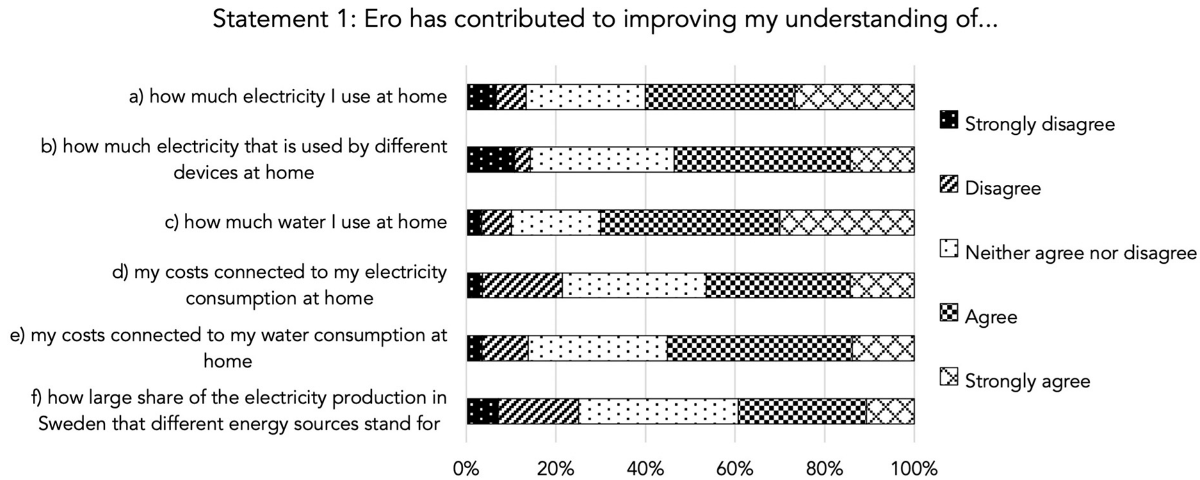

Fig. 4. Agreement to statements in the post survey. Responses in the category “don't know” are excluded (2–4 responses).

how much water and electricity I use in general” (27-M). Another interviewee explained that in his household, they could see that the electricity use of the fridge was “*changing depending on the days when we filled in new groceries in the fridge*” (15-M). One interviewee explained that she had noticed that her electricity use peaked on days when doing the laundry. However, it was the information about water consumption that caused the greatest surprise: “[…] *I was surprised that it's so much even though we don't do anything* […] *we don't water the garden, we don't wash cars, we do nothing. Still there will be a few litres of it. Surprisingly much*” (23-M).

Unfortunately, since the water screen (Fig. 2, left) was only updated once a day, this made the information difficult to act on: “[…] *so, for me I cannot really distinguish* ‘*Was that because of the shower? Was it because of the dishwasher running? Or because of the washing machine?*’” (15-M). However, the electricity screen also lacked some details. For instance, it was difficult to see the exact consumption level at a specific time, information about costs was missing and several interviewees asked for consumption data over a longer time perspective to be able to see trends.

Ero introduced new material elements, which in turn supported the forming of new competences. Two interviewees explained that before they started using Ero, they were not sure of whether the floor heating was on or not. Since neither of them wanted to use the floor heating, they were positive about being able to “*see that it really was off* [*in Ero*]” (12-F).

Electricity consumption data was available for five or four devices per apartment only, and several interviewees were interested in receiving the same information for other devices. Some found it relevant to add more material elements (smart plugs) to improve their knowledge about the electricity use of individual devices.

Through the electricity threshold in Ero, the participants were introduced to a new meaning connected to their energy use: to stay below the threshold. In some cases, competences and meanings about the energy system also changed as an effect of the study. One interviewee explained:

> […] *one thing I didn't know before anyway, it was that electricity consumption, or the supply, changes over the 24 hours of the day. I didn't know that it could be better to do the laundry at a certain time rather than another*
>
> (29-F)

However, this learning was probably more generally connected to the participation in the study than specifically using Ero. Eight interviewees expressed that Ero had contributed to raising their interest or engagement in electricity and water consumption. Another interviewee

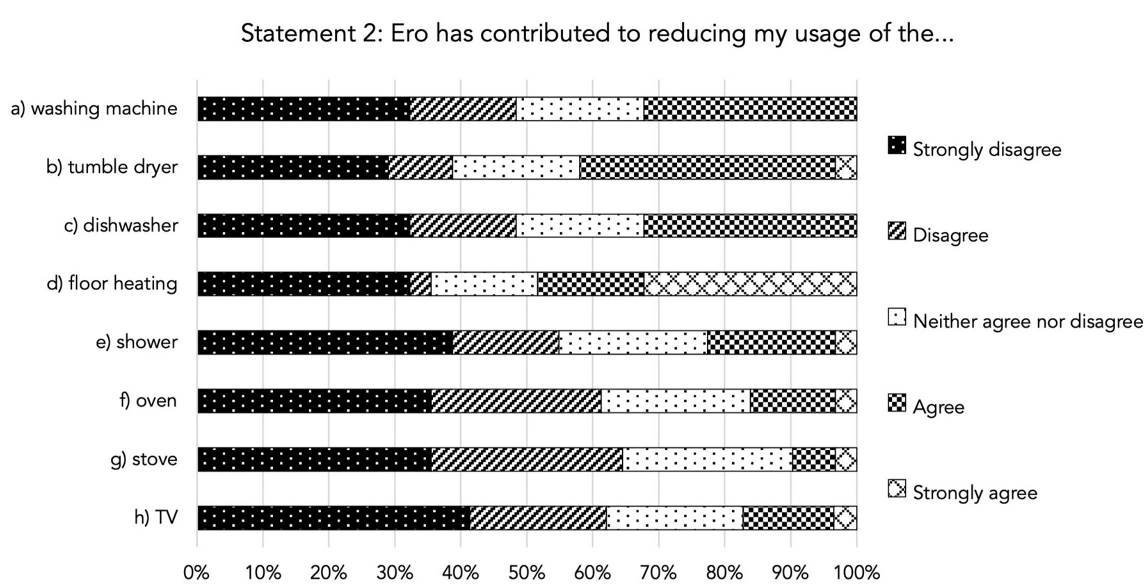

Fig. 5. Agreement to statements in the post survey. Responses in the category “don't know” are excluded (1–3 responses).

experienced that his interest had remained unchanged because he could not see the impact of changing practices and, as he expressed it: "*It's never telling me that I'm good!* [*laughing*]" (26-M). Finally, one interviewee found that his interest was reduced as a result of the limited functionalities and control opportunities in Ero.

4.4. Reconfiguration and time-shifting of practices

In a few cases, changes in elements induced by the Ero app contributed to changing energy-reliant practices. According to the post survey results presented in Fig. 5, the most reported devices to be reduced in use because of using Ero were the floor heating and the tumble dryer. Two interviewees shared:

> [...] *in the beginning, before I got this app, I had the floor heating on at all times, but then I saw the consumption and thought "that's a lot actually, consumed on the floor heating". That's why it's generally turned off right now*
>
> (15-M)

> *I don't do a lot of cooking. The electricity I use is hard to minimise and my washing – I need to do that. So, the only thing I could change was the dryer because I can dry clothes on the balcony and in the bathroom. That was the only hack for me*
>
> (19-M)

Furthermore, about one third of the survey respondents agreed that Ero contributed to reducing their use of the washing machine and the dishwasher (see Fig. 5). A few interviewees mentioned thinking more about how they use water and tried to take shorter showers, lower the temperature while showering or avoid leaving the tap running when doing the dishes. Some strived for running the dishwasher or washing machine only when full, using eco-programs to a greater extent, not using more lights than needed and avoiding leaving the TV on in the background.

Staying below the electricity threshold was generally considered difficult. Since it was based on the households' average electricity use, it became very low for those who already had a low consumption. This resulted in some frustration among the participants, who did not understand why they were above their threshold so often. One interviewee shared: "[...] *so the only time I see it is when my threshold is above. Maybe I'm below on times when I'm not opening the app* [...] *I always see it when I'm the bad guy.*" (26-M).

As seen in Fig. 6, a majority of the survey respondents did not use the electricity threshold in Ero to plan any energy-reliant activities in their everyday. Only one interviewee mentioned using the electricity threshold to plan when to start the dishwasher. The difficulty to adapt energy-reliant practices depended on different factors. First, several interviewees experienced a lack of flexibility in everyday life to change energy-reliant practices. One interviewee discussed that working in shifts with varying work hours made it complicated to time-shift practices. Another interviewee reflected that he was more flexible before getting a baby. Others mentioned having fixed times when they eat, making them less willing to change cooking practices.

Second, some interviewees mentioned the size and layout of the apartment as barriers to time-shifting or reconfiguring energy-reliant practices. For instance, having an open plan kitchen and living room restricted the possibilities to run longer wash programmes and leaving dishes for later because "*then you have it in the living room*" (23-M). Thus, in some cases the spatial properties of the dwelling limited the willingness to change practices as this element was linked to the meaning of having a tidy and noise-free home, a link that seemed difficult to break.

Third, the motivation to adapt different practices involving electricity and water use was negatively affected by a lack of incentives and perceived impact. Several interviewees asked for clearer communication regarding the impact of their efforts, both concerning financial and environmental aspects. Two couples discussed that before taking the decision to adapt the time of doing laundry, they wanted to know the benefits of doing so. For many interviewees, it seemed that saving money was more important to them than reducing the environmental impact. One of the interviewees shared:

> *When I think about the whole study, I thought "it's important to save energy and it's important for the environment", but really, I didn't think about that, I thought about whether I saved something myself.*
>
> (27-M)

Fourth, it was clear that the Ero app itself did not provide enough support for time-shifting or reconfiguring practices. Rather than strengthening competences and positive meanings, Ero sometimes caused frustration instead. Several interviewees mentioned the need for better guidance, preferably personalised with tailor-made advice based on your specific settings. It was also discussed how different individuals have varying understandings and interest in their energy and water

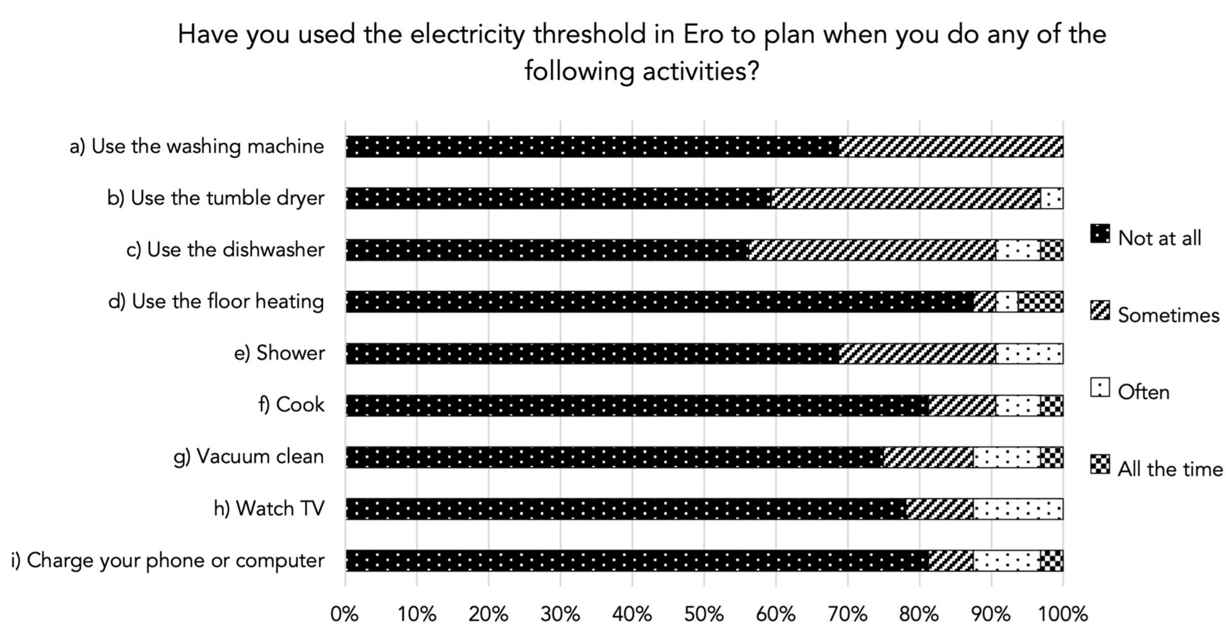

Fig. 6. Responses to question in the post survey.

consumption. Therefore, Ero needs to be able to adjust to different knowledge levels and preferences. This also concerns the frequency of receiving notifications as some participants found them stressful. Furthermore, a few interviewees reasoned that to plan their energy use, they needed a better forecast that communicates the availability of their preferred energy sources.

Fifth, although not as frequently mentioned, the lack of control possibilities in Ero to some extent seemed to pose a barrier to changing practices. For instance, one interviewee reasoned that he was not willing to accept any changes that would have a negative impact on his daily life, like giving up floor heating: "[…] *I mean it was winter and it was minus degrees and it* [*Ero*] *started telling me to switch off the floor heating* [*laughter*] *and I was like… no way.* [*laughter*]" (26-M). Rather than having to turn it on and off himself, he explained that it would make more sense to him to have the floor heating scheduled to be off during work hours and on when he is at home. In that way, meanings of comfort connected to using the floor heating would not have to be sacrificed. Another participant explained that enabling devices that are often on standby to be turned off through the app probably would help him to reduce his energy consumption significantly. Other suggestions for added control in Ero regarded the room temperature, fridge temperature and lighting. However, there was varying interest in being able to control more devices through the app. Three interviewees discussed that the usefulness of being able to control devices via Ero rely on that you also receive consumption data for those devices. Safety aspects connected to the possibility of controlling devices through an app were also discussed, both positively and negatively.

The barriers discussed by the interviewees regarding changing energy-reliant practices at home are summarised in Table 2.

Table 2
Perceived barriers to changing energy-reliant practices at home, discussed by the interviewees.

Barrier	Factors mentioned by interviewees	Example quotes
Lack of flexibility in everyday life	- Limited flexibility when having children - Limited flexibility when working in shifts - Eating at fixed times	"[…] *when you have a baby, and you need to do the laundry… yeah then you need to do it*" (15-M) "*I am working in different work hours, so it is really complicated for me* [*to plan the use of appliances according to the electricity threshold*]" (19-M)
Limitations in size and layout of the dwelling	- Lack of space to hang the laundry - Unwilling to leave dirty dishes exposed in the kitchen when combined with the living room - Unwilling to run longer wash programs due to noise disturbances in small apartment with open floor plan	"*Personally, for me it's most difficult to let go of the tumble dryer, partly because I don't have the space to hang* [*the clothes*] *and air dry and partly that it's not weather outside to hang it out. I grew up in a house when I lived with my family and then we always hung the clothes outdoors. I don't have the same possibility here and I find it difficult to break – I haven't come up with any idea how I can do otherwise.*" (10-F)
Lack of incentives and perceived impact	- Not seeing financial or environmental effects of changing practices - Experiencing one's own energy use as insignificant with small saving potentials - Missing financial incentives - Missing environmental incentives	"[…] *when I looked at my bill it felt like even though I reduced my consumption it didn't feel like I saved much money* […] *I felt that I might use too much water and that I could shower a little shorter and use less water, but then at the same time I thought that it didn't cost that much extra.*" (27-M) "*What does it mean if you plan up when you do laundry and wash dishes and how much electricity and money can you save in a year? So you can see a little more clearly what impact it has*" (29-M)
Lack of guidance	- Electricity threshold not clearly communicated - Lack of concrete, personalised advice - Different knowledge levels and preferences regarding how information is presented	"[…] *I think the way it was, it was always telling me that I'm using too much, so you get a little bit frustrated because I… It doesn't help me change that, so it just tells me 'Hey you're an idiot'* [*laughter*] *and then I, you know can't really, can't really change anything so…*" (26-M)
Lack of possibilities to control devices through the interface	- Not possible to schedule devices, such as floor heating - Not possible to turn off devices on standby in the app - Consumption data only available for some devices	"*If I'm going to save electricity on something, maybe it's all these devices that are on standby* […] *I would like to measure that whole package to see, because I suspect that they draw almost as much power in standby as they do when they are on* […] *So if I were to save power, I would sort of have the option of turning them off when I'm not at home.*" (31-M)

5. Discussion

This study explored how a HEMS prototype, Ero, was used by households in a multi-residential building in Sweden. The aim of the study was to increase the understanding of how households perceive HEMS and their possibilities to change practices in everyday life to support a more sustainable energy system. This paper contributes with insights about how end-users are willing to adapt their consumption and what may hinder them in changing energy-reliant practices at home. Based on this, design opportunities for future HEMS are discussed. The trial itself is a small simulation of how users could interact with HEMS in a future smart grid to achieve demand-side management.

5.1. Changes in practices

In line with outcomes from the testing of its former version [15], many of the participants in this study stated becoming more aware of their energy use in general and specifically connected to different functions at home from using Ero. An overview of how Ero had impacted daily practices identified in the interviews is illustrated in Fig. 7, adapted from Christensen et al. [34]. Temporal rhythms related to life situation and work hours are not included in the figure.

Ero introduced new material elements and contributed to changes in competences and meanings about energy and water use at home as well as the energy system in general. In some cases, this contributed to changes in practices, such as decreasing the use of the floor heating and tumble dryer. In other cases, new insights from using Ero did not lead to any reconfigurations or time-shifting of practices. Reducing the use of some devices and functions or using them in a slightly different way (for instance only running full dishwashers or taking shorter showers) were more common outcomes than time-shifting practices.

The appliances that were most reported to be time-shifted based on the electricity threshold was using the dishwasher and tumble dryer (see Fig. 6). This is in accordance with several previous studies identifying dishwashing and laundry as relatively flexible for time-shifting in relation to other domestic practices [18,24,25,27–29]. Although few

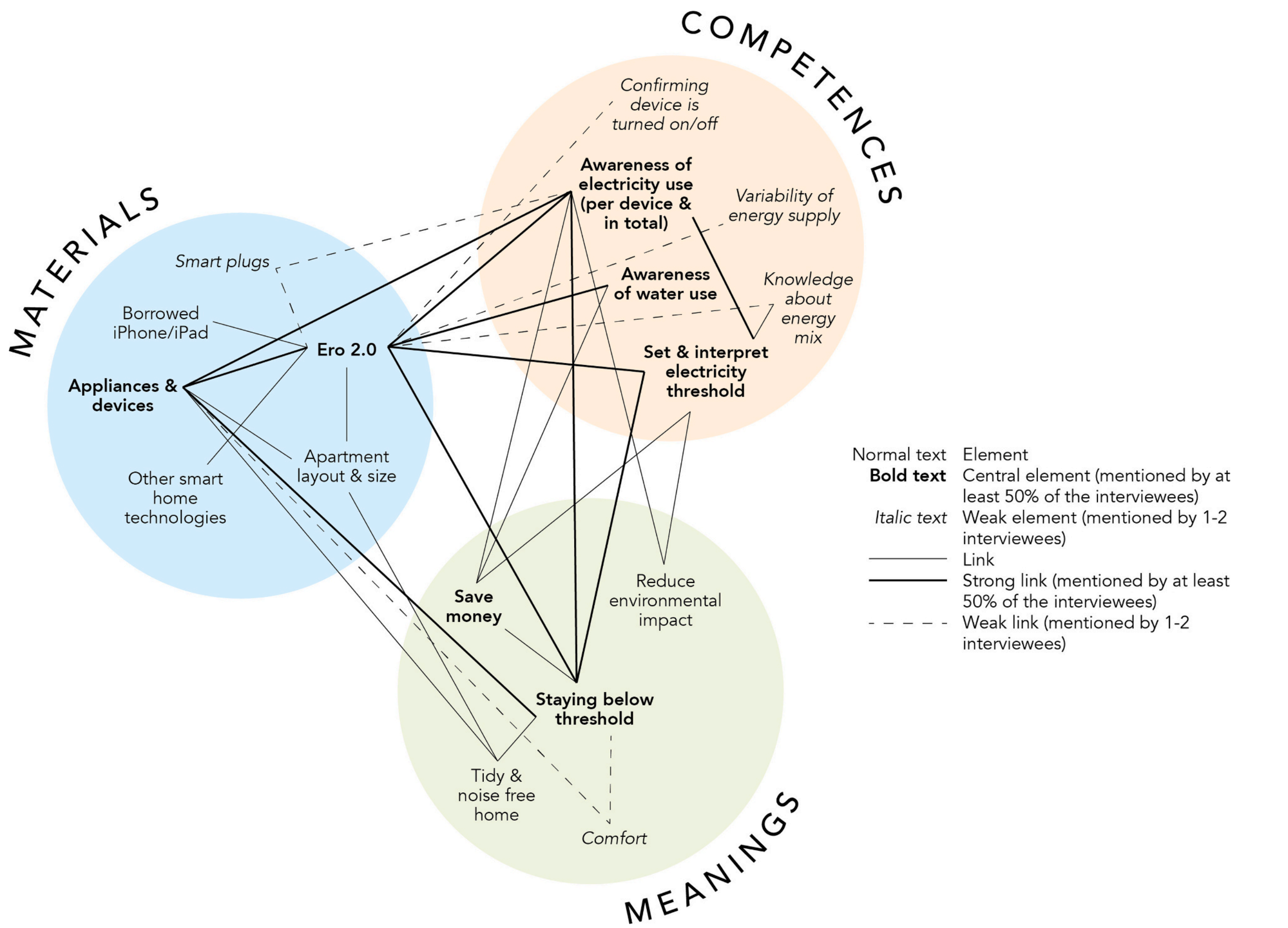

Fig. 7. Practice elements and their links identified in the interviews.
Adapted from Christensen et al. [34].

reported using the electricity threshold to time-shift floor heating, the survey and interview results both indicated that this was the most common energy-reliant function to be reduced or even eliminated during the study.

In some cases, Ero seemed to contribute to changes in practices involving water use, such as shorter showers and reducing the temperature. Some participants even reported using the electricity threshold to plan when to shower (see Fig. 6, statement 4f), although this practice relied on the use of district heating rather than electricity. However, time-shifting practices using district heating is also relevant and could be supported by a separate "district heating threshold", similar to Ero 1.0 [15]. Households' flexibility in the use of district heating supported by smart technologies has been discussed in previous research, focusing on space heating [37,38]. However, there is not much research on how to enable flexibility in district heating connected to households' water use and apart from Ero 1.0, we have not found other examples of HEMS including a district heating threshold. How to better develop personal energy thresholds for both electricity and district heating is therefore an area that could be further explored.

5.2. *Difficulties of changing practices*

Some of the identified barriers to adapting energy-reliant practices have been discussed in previous research. Selvefors et al. [39] have previously highlighted how competing goals in everyday life often makes it difficult to prioritise energy savings. The limited flexibility of households with children to shift energy use outside of peak hours has also been identified in previous research [24,25]. Furthermore, practices have previously been explained to depend on collective temporal rhythms such as work hours [26], which in the present study were found to limit the flexibility for some participants.

The identified limitations regarding apartment size and layout indicate that the transition to future smart and sustainable energy systems also requires smart designs of dwellings to support flexibility in domestic energy use. Reisinger et al. [13] have previously mentioned *space* as one of the design dimensions to be addressed in the design of future smart home solutions. However, the spatial aspects related to the layout and size of dwellings is an area that to date has received little attention in smart energy research. Increasing dwelling sizes to reduce disturbances from appliances is clearly not an energy-efficient strategy. Designing the apartment layout differently might prevent some of the problems highlighted, although open floor plans are often the most space efficient option. Thus, future HEMS may also need to make trade-offs regarding the best time to use appliances considering both the status of the energy system and causing the least disturbance for the household. Another approach to address these issues could be through improved design of appliances, for instance by reducing noise levels. How to better adapt dwellings and appliances to support flexibility in households' energy use is an area where there is an evident need for further research.

Because of not seeing any effects despite adapting some energy-reliant practices, many participants became disengaged and lost interest in the app during the study. Similar findings have been presented in previous research [15,30,34]. One way to communicate the benefits of time-shifting and reductions in energy use could be to visualise environmental and financial impacts in a wider perspective, as suggested by some of the interviewees. This could mean communicating savings over longer time perspectives or zooming out from the individual household and presenting collective impacts that involve all households in the same building or neighbourhood.

Although the electricity threshold in Ero was appreciated by many participants, it was generally not clear what it meant and how it should be acted upon. Better guidance was therefore requested, preferably personalised for the specific user. This is in line with previous research highlighting the need to provide information that is "*actionable and meaningful with respect one's own specific situation*" ([31], p. 1654). Based on previous work by Strengers [40], Hargreaves [41] recommend going beyond energy feedback and exploring other forms of practice feedback that are more integrated with social practices. Furthermore, including more positive feedback and enabling users to adapt the frequency of notifications also seem important. Additionally, the threshold itself needs to be further developed to avoid punishing households who already have a low electricity consumption.

Finally, the lack of control possibilities in Ero was raised as one reason for not finding the app useful and a factor limiting the opportunity to become more "energy flexible". Further research studying the effects of including more control and automation of devices in HEMS is therefore needed.

5.3. Supporting flexibility in energy use for a diversity of people

The participants were generally positive about including not only electricity but also water consumption in Ero and some also wished to include heating consumption data. Not limiting the app to electricity use but providing a wider perspective on consumption might contribute to making the app relevant for more users and possibly prevent fading interest in the app over time. Friis and Christensen [27] previously highlighted that combining several smart grid interventions may increase active participation in time-shifting consumption. Especially, combining a smart home system with local energy production such as home-installed PV panels seem highly relevant. Gram-Hanssen et al. [28] found that among households owning PVs, time-shifting energy use was widespread, and these households also considered themselves to be more aware of and interested in their energy consumption.

During the testing of Ero, the participants assumed different roles. A few had a high interest in their consumption data and actively monitored their consumption during the study. Some of them wished to dig even deeper into the data and a few of them also used other smart technologies at home. Still, their high interest in consumption data and smart technologies did not necessarily contribute to changes in their everyday practices. Thus, these participants shared many similarities with the image of Resource Man [17] but in accordance with findings by Verkade and Höffken [18], the introduction of an energy management tool was not always enough to induce changes in their energy use. Instead of becoming a tool for adapting consumption, for some participants Ero mainly became an awareness tool, which is in line with findings from similar studies [15,31].

Other participants wanted better guidance for how to adapt their energy use without having to immerse themselves in information about energy. These participants shared similarities with a role previously identified by Renström [19], in which the participants were willing to sacrifice some of their needs to save energy if they were told what to do. Clearly, competences and interest regarding energy use and smart home technologies varied greatly among the interviewees. These findings highlight the importance of adjusting the interface to varying knowledge levels and preferences, in accordance with findings from previous studies [13,20].

Overall, using the concept of an electricity threshold to communicate more and less favourable times for using energy seems to hold some potential for engaging households in their electricity use. However, it requires thorough consideration and further development of the threshold in order to better support flexibility in energy-reliant practices. The threshold needs to be simply understood and acted upon as well as rooted in the specific context of each individual user. However, as already highlighted in previous literature, flexibility in energy use depends on a number of factors that are not likely to be influenced simply by the introduction of smart home technologies. Future HEMS therefore need to be combined with dwelling designs, appliance designs and wider system changes that allow everyday practices to be flexible. Still, the question remains whether potential energy savings and shifted loads induced by smart technologies in the end will outweigh new environmental pressures from adding more devices and increasing the connectivity of appliances in the home, possibly triggering new expectations of comfort and convenience. As previous research has noted, there is a need to consider how to promote both desirable and less energy intensive ways of living in the smart home [7,8].

5.4. Limitations

This study was conducted in a Swedish context, including households living in rental apartments. The results rely on the participants' own reporting from interviews and survey data, rather than measured consumption data. This allowed us to get deeper insights about experiences and perceived possibilities to adapt energy-reliant practices. However, it is impossible to make conclusions about the extent to which changes actually were implemented. The testing period of two and a half months also limits the possibilities to identify and evaluate long-term changes from the field trial. Furthermore, the study was conducted before the current energy crisis and the results may have become different if the trial was conducted today as many people have become more concerned about their energy use. Another limitation was that some participants used Ero on a borrowed device, which seemed to contribute to lower engagement in using the app.

6. Conclusions

This paper contributes with insights about how the use of a HEMS, featuring a personal threshold on energy use, was perceived and used by households in everyday life. The findings provide a greater understanding of the influence on energy-reliant practices at home and the perceived barriers to changing them in order to use energy more sustainably. Finally, this article provides recommendations for the design of HEMS, which are relevant to future developments of smart energy systems.

The evaluation of Ero showed that many participants experienced becoming more aware of and engaged in their electricity and water use. To some extent, Ero also contributed to changes in energy and water-reliant practices, mainly by inducing reconfigurations and reductions of certain activities such as using the bathroom floor heating less and hanging clothes instead of using the tumble dryer. To a lesser extent, Ero contributed to time-shifting of energy-reliant practices, which was considered difficult by most participants. Difficulties to change practices depended on several factors: (1) lack of flexibility in everyday life, (2) limitations in size and layout of the dwelling, (3) lack of incentives and perceived impact, (4) lack of guidance and (5) lack of possibilities to control devices through the interface.

This paper concludes that future HEMS need to be designed in a way that adapts to varying levels of knowledge and interest among users and be able to adjust as users' knowledge may change over time. To prevent the system from only becoming a monitoring device, focus needs to be placed on making the information meaningful and possible to relate to in one's own everyday practices. This might be facilitated by adding more possibilities for control through the system than was technically possible in Ero. However, this requires thorough consideration of the environmental impact that the HEMS itself represents. Also, we suggest that HEMS should adopt a broad perspective on consumption, not isolating it to electricity but also including other forms of resource consumption such as heating and water use. Users also need to be able to see the impacts of their efforts to adapt their consumption. Overall, HEMS should communicate through positive stimuli and inspire users in *how* to change practices.

Finally, future HEMS need to be combined with dwellings and appliances whose design can support more flexibility in energy use as well as wider system changes. The design of smart technologies alone cannot achieve the transition to future sustainable energy systems but is only one potential piece of a large puzzle. A systems perspective is clearly needed that addresses different ways of supporting more flexible and sustainable energy use for a diversity of people.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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