Towards Designing Smart Home Energy Applications for Effective Use

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Abstract. To reduce climate change, considerable behavioral changes are required from private households, who often have a low energy literacy and are therefore unaware of the necessary behavioral change.

We introduce a Design Science Research project with the aim to increase energy literacy. To this end, we contribute a theory-grounded design theory for a Smart Home Energy Application based on effective use.

In comparison to previous approaches for designing Smart Home Energy Applications, the design process is user-centered.

We combine semi-structured interviews with a structured survey and a literature review to derive meta requirements and deduct preliminary design principles mapping them to a prototype.

The intermediate results of this study inform research and practice by providing valuable insights on how users interact with a Smart Home Energy Application. The design principles enable the design of information systems allowing for effective use and contribute to a more sustainable energy behavior of households.

Keywords: Energy literacy · Design science · Effective use theory

1 Introduction

As households are accountable for a significant share of the final gross energy consumption (e.g., 28.9% in Germany in 2020 [32]), they are a relevant interest group that needs to be targeted regarding emission reduction to achieve the international climate goals. In the case of private households, the associated necessary Sustainable Energy Transition (SET) translates into a more sustainable energy consumption including heat, transportation and electricity consumption. However, energy is a product fulfilling only functional needs [28] and energy usage is an abstract process not providing any visible feedback [11]. Therefore, energy is considered a low-involvement good, meaning that it only gains relevance in case of shortage, which makes it harder to attain consumers' interest and motivation [28]. This is underlined by various studies stating that energy literacy, the conscious knowledge of energy consumption and consequences, is low [21]. However, the seemingly low energy literacy of citizens contrasts with the importance of

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citizens and the necessity to understand and address their needs in order to successfully achieve a SET (e.g., [31]). Therefore, it is necessary to sensitize citizens and encourage them to actively participate in the energy transition through an understanding and consequently an adaption of their behavior. With this study, we present the first results of a larger Design Science Research (DSR) project [18] aimed at identifying Design Principles (DP) for a Smart Home Energy Application (SHEA) based on smart meter data ensuring effective use by consumers. This study comprises a rigorous description of the problem space derived from interviews, a literature review in the next chapter and a large survey among owners of PV systems, the first derivation of Meta Requirements (MR) and DPs as well as the demonstration of the first prototype. We also provide an outlook on the setup of the DSR project, overall. In particular, this study answers the following research question:

What are the relevant design principles for the development of a SHEA that enables an effective use by users to increase energy literacy?

2 Related Work and Theoretical Foundations

In this chapter, we briefly outline previous studies and findings in the area of energy literacy and associated digital tools. Furthermore, we extensively describe our theoretical foundation within the theory of effective use.

Energy Literacy and IS. The broad term "energy literacy" covers both content knowledge on a cognitive level and citizens' understanding of energy including affective and behavioral aspects [21]. DeWaters et al. [6] define an energy literate person as someone, who is able to take informed actions and make sustainable energy decisions by using her or his understanding of the impacts of energy generation and consumption on the environment and global community. Over the last years, several studies have been published revealing the low level of energy literacy within the population all over the world [22] and the need to do more research on how to increase this level [33]. This is also affirmed by the authors of [36] stating that customers "lack information about the environmental consequences of their choices" [p. 12] preventing them from a more sustainable energy consumption behavior. The authors of [31], for example, investigate how to engage people to participate and change their energy behavior stating that many people are still unaware of the consequences of their current energy behavior. Promoting energy literacy can thus foster a shift in knowledge and perception of energy, thereby facilitating responsible, sustainable energy related decisions and behavior. Therefore, it is relevant to gain knowledge on how to engage the general public for a SET by helping them to become more energy literate.

Information Systems (IS) have been identified as key enablers in the transformation of organizations and the society towards more sustainable behavior as they provide information, which can then motivate behavioral and economic actions [8]. According to the authors of [36], an IS "can distribute information to consumers to influence the use of a physical flow system" [p. 9] enabling them to make informed decisions about their energy consumption patterns. This is consistent with the suggestions of the author of [23] to develop IS to influence individual consumption schemes. Various projects and tools that provide energy feedback to their users and influence consumption behavior are described in the literature (e.g., [5, 26]). While early studies in this research area have focused on dedicated in-home energy displays, recently, studies have concentrated on the use of simple and cheaper mobile SHEAs (e.g., [14, 24, 25, 27, 30]). Even though there are different projects implementing SHEAs to help people understand their energy behavior, they mostly focus on purely capturing and transmitting the data (e.g., [14]), and either face the issue of not being used or evaluated over a longer period of time (e.g., [30]), or they do not measure the actual effect they have on the users' knowledge and behavioral changes (e.g., [27]). While the use of user-engaging designs is already present on the research agenda in other research areas, like customer service (e.g., [15]) or crisis response (e.g., [29]), studies taking a user-centered, theory-based design approach within the household energy sector are lacking, but encouraged by different researchers (e.g., [10, 14]). To the best of our knowledge, there is no structured research on designing a SHEA user-centered with the aim of increasing users' energy literacy inducing more sustainable energy usage decisions. With our research, we contribute to the area of Green IS, which has been established to tackle the issues of environmental problems providing suitable information driven solutions [35]. We provide valuable insights on current user interaction with existing SHEAs and derive preliminary DPs.

Effective Use Theory. To maximize the benefits of IS, they must be used effectively [2]. A basic assumption behind effective use is related to the purpose and nature of an IS. It assumes that systems are not used just for the sake of using them, but to support other tasks and achieve some other goals [13]. For this matter, Burton-Jones et al. [2, p. 633] established the effective use theory defining "effective use as using a system in a way that helps attain the goals for using the system." Effective use is an objective concept, i.e., it focuses on observable behavior instead of what is perceived by the users (which would be perceived usefulness referring to a user's expectation or perception). One central challenge is the measurement of those objective qualities, which could be assessed in terms of performance. Effective use is constructed on three hierarchical dimensions stemming from representation theory [2, 3, 34]. Every lower level is necessary, but not sufficient for the next higher level. At the start, an (1) unimpeded, intuitive access to and interaction with the system's representations is necessary (*transparent interaction*) allowing the user to (2) obtain representations, which reflect the underlying represented domain faithfully (*representational fidelity*). Finally, the user is enabled to (3) act upon this faithful representation to improve his or her state (*informed action*). In our case, users need to be able to easily access and intuitively navigate through the SHEA (transparent interaction). Such a seamless interaction saves time and helps users to focus on the system's information, which is critical to an effective performance [9]. On the contrary, effectiveness is reduced if users are not able to find and appropriately use features needed to gain knowledge about their energy behavior. Representational fidelity then fosters the effectiveness by increasing the understanding and reducing uncertainties through an appropriate presentation of the relevant information. In our case, this means incorporating those features and their forms of representation that help users to understand their energy behavior. If representational fidelity is high, users do not need to spend time verifying the presented information. Finally, users reach an increased state within the energy domain, thereby reducing errors and increasing effectiveness if the level of informed action is high. In our case, this means that users are enabled to evaluate their energy behavior, being able to make sustainable energy decisions. For example, this could include increasing their share of renewable energy by using energy at the time that energy is generated (on a sunny day during the day instead of at night), or the decision to install own renewable energy generating capacities. On the contrary, an ill-informed action might lead to spending time on recovering from errors. In conclusion, transparent interaction activates the informing potential of an IS, representational fidelity then ensures this potential is positive, and informed action leverages it [20]. While existing research on SHEAs for increased energy literacy mainly focuses on the representational fidelity by just showing the data to the users (e.g., [14]), we propose to expand this focus to the level of informed action by measuring the effects of the SHEA usage on energy literacy and behavioral change. To address this, we propose to actively engage users in the design process and build an artifact based on the effective use theory. In general, the challenge when designing an effective use system is to learn what effective use involves and how this can be achieved and measured [7]. We describe our corresponding methodology in the next chapter.

3 Research Methodology

Figure 1 shows the used general DSR Methodology based on Kuechler and Vaishnavi [18] and the design cycles based on Hevner et al. [17]. In this paper, we summarize the findings of the first three steps of Design Cycle One, namely the awareness of the problem, the suggestion and the development of the prototype (boxes in grey). We argue that the DSR approach is well suited for our research question as it can seek a solution to a real-world problem, which is of practical interest [17]. Moreover, the DSR approach allows us to combine the existing knowledge within the areas of energy literacy and SHEA design with theoretical foundations of effective use. Also, this approach allows for an execution of build-and-evaluate-loops to test the effective use of our developed artifact and improve it, correspondingly [17]. This provides a rigorous grounding and enables us to make a contribution to the existing knowledge base. Our DSR project is set up over three design cycles. In the first design cycle, we test our artifact in a behavioral laboratory experiment. In the following two design cycles, we then test it in different field settings over an extended period of time. Overall, our research project aims to ultimately contribute a design theory, delivering prescriptive knowledge for designing SHEAs that increase users' energy literacy leading them to more sustainable energy decisions through effective use [16].

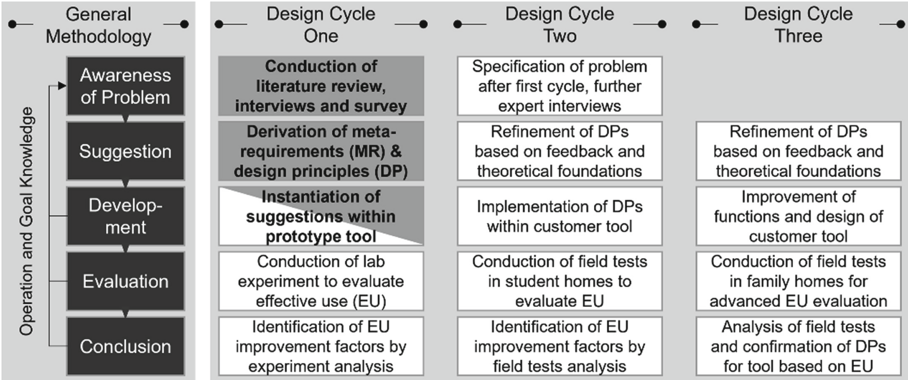

Fig. 1. Design science research methodology (based on Kuechler and Vaishnavi 2008).

4 Designing a Smart Home Energy Application

In this chapter, we report on the results from the first steps of the described DSR project. We begin by a detailed description of the awareness of the problem and then move on to the suggestion and development phases.

Problem Awareness Overview. To understand potential current issues, we firstly started our research with semi-structured interviews with participants of an existing field study on the helpfulness of a provided SHEA [27]. The participants were asked, for example, if the SHEA has helped them to understand their energy behavior better and if it had led to behavioral changes. Also, they were asked more explicitly about certain features within the SHEA, like those in Fig. 3, and their helpfulness. In addition, they were asked about the interaction with the SHEA, i.e., why they had (or not had) used the SHEA and whether it helped them. Second, to broaden the insights on energy behavior beyond that specific pilot project with few respondents to the general public, we conducted an online survey with home owners possessing Photovoltaics (PV) panels. We focus on this particular group (1) because they have invested in energy generation technology and are therefore more familiar with the subject overall and (2) because owners of PV panels are often provided with a SHEA by the vendor to track their energy generation and consumption. After screening out participants not fulfilling this criterion and participants not giving the right answer to an attention check within the survey, we received 408 valid completed surveys. Participants were asked whether they had access to a web-based or mobile SHEA to track their energy consumption and generation. Furthermore, we asked participants about a) the helpfulness of prevalent features, b) their perceived increase in energy knowledge and behavioral changes since owning a PV system, and c) whether those perceived changes were linked to using the SHEA. The presented survey results in this paper are based on participants, who affirmed that a corresponding SHEA was provided to them. Thirdly, we conducted a literature review in addition to the empirical research to ensure an inclusion of existing knowledge on SHEA solutions.

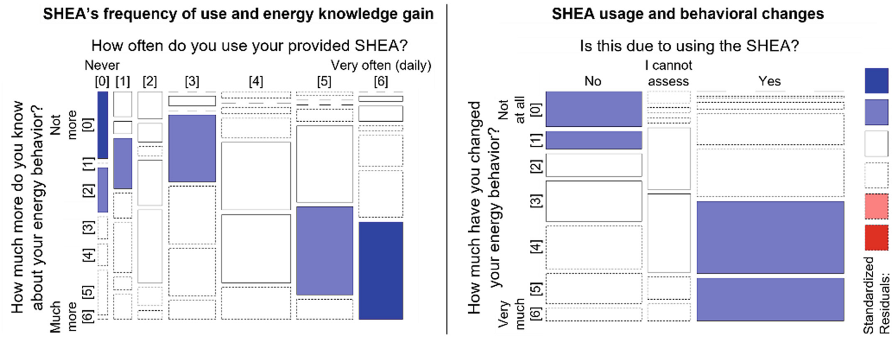

Fig. 2. Connection between energy knowledge/behavioral changes and SHEA usage.

Results: In regard to SHEA usage, the majority of the survey participants stated to use their SHEA frequently. However, more than 10% of the participants never or almost never use their provided SHEA. On the contrary, a majority of the interviewed field project participants stated that they rarely used the SHEA and rather relied on the accompanying weekly reports that summarized their weekly activities. With our user-centered design approach, we aim to address those participants that have not been using the SHEA. Given that a majority of users stated a regular interaction with the SHEA in the survey, we further investigated the perceived effect on their energy literacy. The two mosaic plots in Fig. 2 visualize our results of a statistically significant (0.000 significance level each) dependence between the gain in energy knowledge and the frequency of use of the SHEA (left), and between behavioral changes and the helpfulness of the provided SHEA (right). The shadings visualize patterns of deviation from independence. A blue tile shows that the number of participants within that group is higher than expected assuming independence of the features, while a red tile would mean that the group is smaller than expected. The results of the left plot show that the participants, who stated that they had gained much additional knowledge on their energy behavior since having a PV system installed have mostly used their SHEA on a daily basis (bottom right corner). This dependence can still be confirmed on the second level of the expressions with a lighter shading. In the right mosaic plot, it can be seen that participants stating they have changed their energy behavior very much mostly affiliate this with the use of their SHEA (bottom right corner). These findings indicate that a SHEA might lead to a higher (perceived) energy literacy and induce behavioral changes. However, the associated causality remains to be shown. On the contrary, there is a correlation between participants stating that they have not learned anything since owning a PV system and never having used their SHEA (upper left corner, left plot). In addition, most participants stating they had not changed their behavior do not refer this to using the SHEA (upper left corner, right plot) raising the question of why they do not use a SHEA, yet. In sum, these survey results point out existing issues, which we address with our DPs. To identify features, which are relevant to users and help them to increase their level of energy literacy, we provided the survey participants a list of prevalent features derived from the interviews, the literature and existing solutions, not claiming completeness. To take into account that the participating PV owners might have a range of SHEA of various development levels, we asked, whether participants had access to such features and whether they find or would (if they currently did not have access to that feature) find them helpful or not. With 88% of survey participants finding it helpful, energy consumption (and generation) history is the most important feature, and therefore needs to be included (see Fig. 3). This is followed by the current consumption and an overview of costs and revenues. For example, 80% of the participants have access to the consumption history in their currently used SHEA and find its usage helpful, 8% of the participants do not have access to that feature, but would find it helpful, 12% of the participants have access to that feature in their SHEA, but do not find it helpful, and only 1% of the participants do not have access to that feature and would not find it helpful. The results of Fig. 3 therefore deliver relevant insights for the derivation of DPs.

Feature	I use it and find it helpful.	Not available, but I would find it helpful.	Total: *Found helpful*	Available, but I do not find it helpful.	Not available, and I would not find it helpful.	Total: *Not found helpful*
Consumption History	80%	8%	**88%**	12%	1%	**13%**
Current Consumption	80%	5%	**85%**	13%	1%	**15%**
Costs and Revenues	43%	26%	**70%**	17%	13%	**30%**
Ad-hoc Notification	33%	33%	**66%**	21%	13%	**34%**
Reference Values	19%	38%	**57%**	22%	21%	**43%**
Action Recommendation	17%	40%	**57%**	22%	22%	**43%**
Goal Setting	20%	31%	**51%**	20%	29%	**49%**
Energy Mix	27%	23%	**50%**	20%	30%	**50%**
News Feed	17%	24%	**41%**	21%	38%	**59%**
Comparisons	16%	23%	**39%**	20%	41%	**61%**
Investment Recommendation	12%	23%	**35%**	23%	42%	**65%**

Fig. 3. Evaluation of features

Identified Issues and Meta-requirements. The following issues have been identified throughout the interviews, the survey and the literature review. The interviewees stated that the login burden was very high (**I1**), which already led to an early frustration when needing to find the right login information. In addition, the graphical user interface was perceived non-intuitive (**I2**) by the interviewees as some SHEA features were difficult to find, which led to decreasing interaction with the SHEA over time. The issue of complicated SHEA handling can also be found in literature [12] and was stated within the qualitative comment section of the online survey. These issues conflict with the first level of effective use as they do not grant unimpeded access. The SHEA needs to be designed in such a way that it has an intuitive GUI in order to be effectively used (**MR1**). The interviewees also stated that data was sometimes missing or faulty (**I3**), which is why they did not trust the data. Similar problems were faced in other studies, too [12, 26]. In the survey, some participants stated that they do not use a SHEA because the have privacy concerns (**I4**). Therefore, it needs to be ensured that the data is transmitted privately and correctly (**MR2**) to fulfill the second level of the effective use theory (representational fidelity). Furthermore, the interviewees stated that they did not actively use the SHEA due to boring or non-intuitive data representations (**I5**). Self-explaining data visualizations, with the most relevant information emphasized properly (**MR3**), are important within (energy) learning contexts [19] to prevent information overload and make the SHEA usage interesting and efficient for users. This is confirmed by the survey results. Another major issue identified in the interviews, the literature [1, 14, 26] and the survey is the inattention to users' characteristics and motivation (**I6**). Some of the latter stated that their provided SHEA would not give them any additional information, because they already feel energy literate enough. Others are only interested in cost reductions and can therefore gather the relevant information directly from their smart meter without the need for using a SHEA. Again, these issues impede representational fidelity as the users do not receive enough information relevant to them or the information is not presented in an intuitive way. Therefore, we derive the MR, that data visualizations need to be adjustable (**MR4**), so that users can decide on their own, which form of representation they want to use. Based on that, the SHEA should include user interaction elements (**MR5**) to actively engage them. It should also be possible for users to customize features by selecting them from a list of available features (**MR6**). As identified within the survey results (see Fig. 3), it is, for example, important to include an easy to understand and customizable time-series representation of the energy consumption and generation. Other features are only important to few users but still provide a benefit to some. Interviewees state that they missed actively being given feedback after they had made changes within the SHEA or changed their behavior (**I7**). This hinders the fulfillment of level three of the effective use theory (informed action). We therefore derive the MR of incorporating individualized feedback (**MR7**) and including information on consequences of behavior (**MR8**), which facilitates making informed decisions. Moreover, interviewees complained about non-transparent processes (**I8**) and the high complexity of additional explanations (**I9**), which can also be found in other cases in the literature [1, 12]. This lack of understanding leads to a decrease in SHEA interaction and consequently decreases the ability to take informed action. Therefore, low-complex mechanisms need to be incorporated (**MR9**), and understandable explanations shall be used (**MR10**). This in turn enables users to understand the underlying concepts and therefore, to take informed actions based on the provided information.

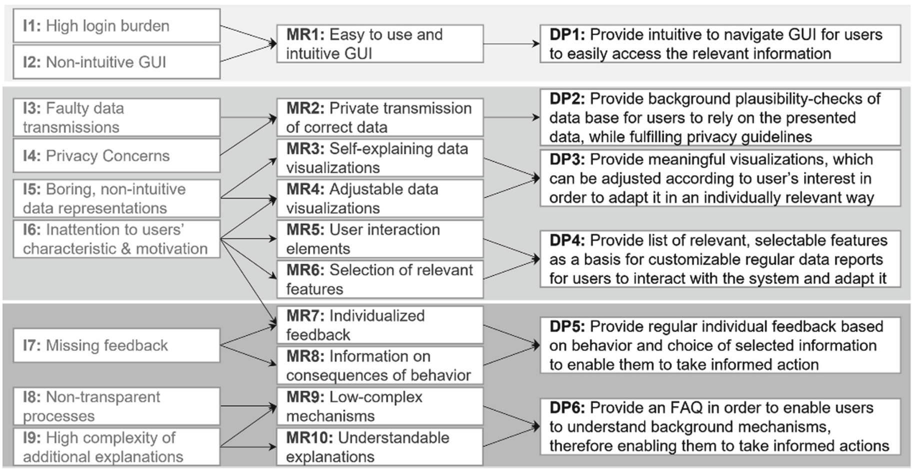

Fig. 4. Issues, MRs and proposed DPs for a SHEA promoting effective use.

Suggestion. To address the nine main issues identified, we derive ten preliminary MRs [17] based on our kernel theory, the effective use theory. From those MRs, we formulate a preliminary set of six DPs following the approach of Chandra [4] that suggests DPs should be action and materiality oriented and therefore "prescribe what an artifact should enable users to do and how it should be built in order to do so" [p. 4043], see Fig. 4 for an overview. The set of derived MRs addresses all three levels of effective use. MR1 addresses users' unimpeded access to the system and therefore, level 1 of the effective use theory. MR2 - MR6 call for data representations, which reflect the underlying represented domain faithfully and therefore, level 2 of the effective use theory. MR7 - MR10 address the ability of users to take informed action and therefore, level 3 of the effective use theory. Due to the fundamental importance of technical aspects, MR1 and MR2 are translated into one DP each (**DP1** and **DP2**). For the remaining four DPs, we can translate two MRs into one DP, respectively. MR3 and MR4 summarize findings about data visualizations and therefore, lead to **DP3**. MR5 and MR6 combine the need of user interaction elements with the concrete selection of features and are summarized in **DP4**. MR7 and MR8 specify the finding that feedback is desired by users, which is reflected in **DP5**. Finally, MR9 and MR10 summarize the insights on the importance to reduce the complexity of underlying processes. Therefore, they are translated into **DP6** to enable users to make informed decisions based on a deeper understanding of the energy domain.

Development. We argue that a SHEA instantiating our DPs increases energy literacy and sustainable behavior of its users because these DPs are formulated based on the rigorous analysis of current issues related to such SHEAs. In the development phase, those DPs have to be instantiated within the SHEA. In Fig. 5, the derived DPs are linked to representations from the first prototype version of the artifact. DP1 is instantiated as a menu tab, which allows for an easy navigation through the most important functions. For DP3, an exemplary data visualization graph of heat costs with highlighted additional performance indicators is depicted. DP4 is instantiated as a list of features, which can be activated via check boxes. For DP5, the prototype shows an example for a direct feedback stating that the user has accepted a certain recommendation that increases renewable energy consumption. DP6 is instantiated as an information icon on each page, which leads to further explanations. DP2 concerns background processes, which are not explicitly depicted.

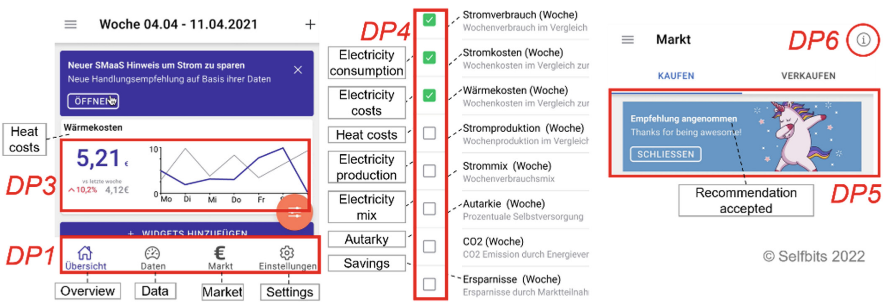

Fig. 5. Instantiation of DPs within SHEA prototype

5 Conclusion and Outlook on Expected Contribution

Improving energy literacy of private households is of central importance for the success of the energy transition. The IS domain can contribute to this task by developing design knowledge on SHEAs that help consumers to better understand their energy consumption and related consequences. Within the introduced DSR project, we aim to contribute a theory-grounded design theory for a SHEA that allows for effective use. This increases the users' energy literacy leading to a more sustainable energy behavior. Throughout the project, necessary features and data visualizations fostering energy literacy are identified and incorporated into the SHEA design. For a holistic view, we combine semi-structured interviews with a structured survey and a literature review to derive meta requirements and deduct a first set of corresponding design principles. Furthermore, we report on the corresponding prototype. The resulting DPs enable the design of a SHEA that empowers users to make more sustainable energy decisions based on their personal circumstances and current energy behavior. Our research provides insights on how users interact with existing SHEAs and which features and design elements are perceived positively by users. The results of this study already inform research and practice and provide valuable insights on how to design corresponding information systems that contribute to a more sustainable society. For future research, a focus needs to be set on actually measuring effective use of our SHEA and establishing a link to energy literacy, including the development of appropriate measurement scales. Another interesting discussion point for future work is to take the perspective of possible SHEA providers, such as municipal utilities, and examine how their goals align with the objective of increasing energy literacy through SHEAs.

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