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Original research article

From context to operationalization: Exploring chances for the integration of social scientific perspectives in life cycle assessments of energy technologies

Mareike Tippe *

German Aerospace Center (DLR), Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, Oldenburg, 26129, Lower Saxony, Germany
Universität Bremen, Bibliothekstraße 1, Bremen, 28359, Bremen, Germany

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A B S T R A C T

The life cycle assessment (LCA) methodology is a well-established tool to assess the environmental impacts of products, services, and technologies. Despite of its standardization, the methodology lacks guidance and formalization for the consideration of behavioral effects impacting the energy consumption related to the usage of technologies. As digital and smart technologies are supposed to play a major role in the energy transition, a consideration of these effects is crucial for the comprehensive assessment of environmental impacts caused by these technologies. In order to address the lack of formalized approaches for the integration of behavioral effects into LCA studies, a qualitative interview study with experts from the social sciences and LCA practice was set up, identifying challenges and chances for the interdisciplinary alignment of the LCA methodology with social scientific approaches. On the basis of the content analysis, the study highlights barriers for the transfer of knowledge between the disciplines and offers insights on challenges faced by practitioners (e.g. lack of time and financing resources or skepticism experienced by peers). Social scientific perspectives and recommendations expressed by the researchers were aligned with the standardized steps of an LCA, providing insights on possible contributions of the social scientific methods to a more comprehensive assessment of environmental impacts caused by energy-using technologies. The interdisciplinary study thereby connects methodological and empirical insights from research practice, enabling the understanding of socio-technical and socio-environmental dependencies in order to assess environmental impacts of energy using technologies in a comprehensive way.

1. Introduction

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As current research and reports from the Intergovernmental Panel on Climate Change (IPCC) [1] show, the need for measures to mitigate climate change becomes more and more urgent. Also in accordance with the goals of the United Nations [2] the need to bring the socio-ecological transition pathways forward and take measures against climate change is constantly growing. Against this background and in order to promote sustainable developments, the United Nations passed the 17 *sustainable development goals* (SDGs) in 2017 [ibid.]. Addressing different human and environmental needs, they call for actions against climate change, resource management and aim to improve people's lives [ibid.].

Sustainable developments have thereby been defined as those that are "meeting the needs of the present without compromising the ability of future generations to meet their own needs" by the United Nations Brundtland Commission already in 1987 [3]. The SDGs from 2017 define different social, economic and environmental targets to be met, addressing various human needs and rights [2]. Next to the general call to "take urgent action to combat climate change and its impacts" (SGD 13), one overarching and recurring topic within the SDGs is the one of a safe energy supply, explicitly expressed in the SDG 7 ("access to affordable, reliable, sustainable and modern energy for all") [2]. When looking at the energy policies and strategies (e.g. of the European Union) of the last years to address the balancing of energy demand and generation whilst integrating more renewable energies, next to storage options as well as efficiency and sufficiency measures, particularly demand side management (DSM) measures have been widely discussed [4–6]. Whilst some measures are of rather technological nature or face feasibility challenges, DSM initiatives that go along with a digitization and 'smartification' of households rely strongly on user involvement and households [ibid.].

* Correspondence to: German Aerospace Center (DLR), Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, Oldenburg, 26129, Lower Saxony, Germany.
E-mail address: Mareike.Tippe@dlr.de.

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Whenever there are defined goals – like the SDGs or other sustainability targets – there is also a need for forms of benchmarking or measuring the success of actions taken to reach them. In the context of sustainability, this poses a special challenge, as most sustainability concepts and definitions include social, environmental and economic aspects, being referred to e.g. as pillars, dimensions, areas, and so on [7]. This means, that not only environmental, but also social and economic matters are addressed and have to be taken into account, when sustainable developments are to be achieved [7].

As for example the review by Farghali et al. [8] additionally shows do also renewable energies and not only conventional ways of energy production have diverse social, economic and ecological impacts. These need to be assessed and addressed sufficiently when there is the aim to decarbonize energy supply and reach sustainability goals. As sustainability concepts have come a long way [7], there are nowadays various guidelines and options for assessing and reporting the achievement of sustainability goals [9–11]. While life cycle assessments (LCAs) [12–15] are an established method for assessing ecological impacts and life cycle costings (LCC) (comp. [16]) also offer various options for assessing the economic dimension, assessment methods for social sustainability like social life cycle assessments (sLCA) [17] are still comparatively at their beginning. Whereas these assessment methods are often delineated in disciplinary and dimensional terms, entire related interdisciplinary research fields such as socio-ecology, socio-economics or ecological economic research illustrate the overlap of the here often supposedly separable dimensions. Interdisciplinary research can thereby be understood as "a mode of research [...] that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice" [18]. In these interdisciplinary research disciplines, the focus is consciously put on researching the interactions between the 'spheres'. Whilst a spotlight is placed on inter-dependencies, the more implicit they are, the more difficult it is to analyze and integrate these inter-dependencies in research, models and concepts.

As discussed above, current energy policies and strategies to bring the transition towards climate friendly and sustainable energy supplies forward rely on a twofold of finding and implementing technological solutions whilst promoting energy system friendly behavior on the demand side. When it comes to the environmental assessments of these DSM strategies it becomes obvious, that the influence of human behavior needs to be considered when aiming at a comprehensive impact assessment and effect evaluation. Concerning the matter of accounting for user behavior, though, it was shown e.g. in Tippe et al. [19], Pohl et al. [20,21], Stermieri et al. [22] and Di Polizzi Sorrentino et al. [23] that the quantification and operationalization of behavioral effects with regard to related environmental impacts (EI), has posed a major challenge and still does so.

In Tippe et al. [19] approaches that were used to operationalize behavior were identified. Also, Stermieri et al. [22] conducted a comprehensive review of LCAs on ICTs. The challenge of addressing behavioral effects already begins with the fact that within the ISO norms 14040 and 14044 [12,13] currently no commonly agreed on approaches or set regulations on the operationalization of behavior in LCAs are presented. The above cited review studies demonstrate that the lack of guidance results in a broad selection of behavior operationalization approaches, which decreased inter-comparability of studies but also can also strongly influence the study results [19,22]. This diversity of approaches discussed in the reviews is also reflected in recent LCA studies of information and communication technologies (ICT), but also when assessing smart, DSM or residential technologies. With regard to the assessment of ICTs, for example, Suski et al. [24] conducted an online survey on streaming behavior whereas Bodelier et al. [25] chose a mixed method approach that included "data logging via routers, daily experience sampling surveys, and semi-structured interviews" (p. 1) in order to model the usage of streaming platforms. Also, Tabata and Wang [26] performed an LCA with a focus on CO2 emissions of music and video streaming. They, though, referenced diverse online surveys and statistical analysis in order to consider impacts related to user behavior [ibid.]. Concerning the conduction of LCAs on the usage of digital services in general, Istrate et al. [27] defined a user "archetype" (p.2), that was set up based on average values also taken from statistical surveys. The examples of Istrate et al. [27] and also Tabata and Wang [26] demonstrate first of all that there is a need for quantitative data sets on user behavior; secondly, though, they also reveal that LCAs and the quantification of behavioral effects in these cases have not been conceptualized as comprehensive study, but as separate ones. The latter point of a common conceptualization of online surveys and LCA approach can be found in two studies by Pohl et al. [28,29], that include user motivation and sociodemographic factors [29] and the investigation of average system setups [28]. Concerning the assessment of residential DSM strategies in general, in some cases users or their behavior are not mentioned at all, but household averages are used as input data right away and/or if at all combined with pessimistic and optimistic scenarios [30,31]. This overview of identified approaches indicates and underlines clearly three important shortcomings:

1. There is a lack of guidance which makes is necessary for practitioners to choose the operationalization approach themselves.
2. The step of quantifying behavioral effects is crucial in order to consider their influences on the EIs.
3. With some above mentioned exceptions, the LCA methodology and social scientific approaches have so far rarely been coupled or conceptualized together within studies. This leads to the dependency on of LCA practitioners on reliable data sets suitable for their purpose.

As LCAs can vary strongly in their goals and scopes, it can be argued based on these reviews and recent studies that for an enhanced operationalization of behavior within the assessment of the use phase of technologies it will probably be not sufficient to propose one single generic methodological approach (comp. [21]). Nevertheless, it can be considered necessary to propose and test more and broader approaches for a refined assessment of behavioral effects associated with the use phase of technologies. This is especially important if the technologies are particularly strongly defined by the consumption of energy for their operation or are generally part of people's everyday lives (e.g., in household contexts).

Against the threefold of review/overview studies, LCA practice itself as well as the lack of guidance in LCA norms and standards discussed above the need for more explicit guidance in behavior operationalization becomes obvious. Whilst literature reviews can provide an overview of research results, the actual research process and scientific practices with their implicit dynamics and the decision making behind methodological approaches can only partially be deduced within a review process. Prior to the actual development of a framework, there is a strong need for understanding of the LCA-sided handling of the behavior operationalization process and the related scientific practices. Therefore, the work presented here is specifically dedicated to this side of the research practice and the challenges of knowledge and data transfer between ecological and social science research in the energy sector, addressing the research gap of knowledge transfer between social science and LCA practice as well as challenges and chances for enhanced behavior modeling approaches.

Understanding how LCA practitioners as well as social/behavior scientists approach the investigation of technology related behaviors – and their respective environmental effects – is crucial for the development of enhanced operationalization approaches in the future as called for in [19,22,23] or [32]. As argued already in Tippe et al. [19] behavior in (smart) homes can provide a fitting test case for the investigation of behaviors, as routines, habits, and dynamics vary strongly from household to household.

This is why similarly to Tippe et al. [19], the research on and assessment of domestic spaces equipped with smart home technologies (such as smart meters, feedback displays or automation concepts — collectively referred to as smart home technologies (SHTs), from now on) were used as case studies.

In this research a focus was put on understanding knowledge gaps and knowledge transfer, through the eyes of LCA practitioners and social scientists. In order to comprehend informational needs concerning the quantification of behavioral effects and their respective EIs as well as to be able to rely on hands on research experiences, expert interviews were conducted to approach these questions, which are further explicated in chapter 2.1.

The novelty of the here presented study lies first of all in the chosen approach of a two-stranded and comparative interview study. So far conducted studies that investigated behavior operationalization (e.g. [19,22,23]) based insights and recommendations solely on literature, but lacked the perspectives of practitioners and experts. Whilst Suski et al. [32] incorporate perspectives from practice theory into their LCA, perspectives from science and technology studies (STS), ethnography and transformation research addressed in this work are still providing a more comprehensive overview of diverse social scientific perceptions and theories applicable to technology adaption and usage. The latter could in the future not only contribute to an enhancement of the LCA methodology but to a general better understanding of socio-ecological inter-dependencies of the energy transformation.

2. Methods

Within this section the research questions and the methodological approach are presented. The general context of this research on LCAs is the inter-correlation of EIs of technologies, and the way they are used as well as how interdisciplinary perspectives can contribute to an enhanced sustainability assessment. SHTs were chosen as an example since the home is a highly individual space where people live and behave differently [33–36]. They, therefore, offer the opportunity to investigate potentially very diverse use patterns and overall (household) practices which in turn result in according different EIs .

Semi-structured qualitative expert interviews were conducted in the first step, in order to gain interdisciplinary insights on researchers experiences and opinions. Compared to, for example, literature reviews the aim of this research was to gain a deeper understanding of the research practices and processes. Also, requirements and recommendations were gathered that can in the future contribute to the development of approaches that pay tribute to the inter-correlation of social and environmental effects (called for by Suski et al. [32], Tippe et al. [19] and Pohl et al. [20,21]). The general outline of this research is presented in Fig. 1.

In reference to the 32-item list *Consolidated criteria for reporting qualitative research (COREQ)* [39], all items on this list are addressed comprehensively in Table 5 in the appendix.

2.1. Research questions

The overall topic addressed in this research is how behavior (in smart home environments) can, to an enhanced degree, be operationalized in LCAs by the means of considering interdisciplinary findings and requirements in the future. In order to assess the impacts of an energy-dependent technology on the environment the interdependency of behavior and environmental effects has so far often been considered only in simplified manners [19,22] and should therefore be further investigated.

As the ISO norms 14040 and 14044 [12,13] do not provide any frameworks on how to operationalize or consider behavioral aspects in LCAs, these decisions have so far been left to be made by LCA practitioners.

This means that the first research question (RQ1) that has to be posed is the following:

- *How did LCA practitioners come up with their operationalization approach by interpreting and processing knowledge on behavior and practices?*

The focus of the analysis was identifying the challenges faced and the corresponding approaches to overcoming them. Particular attention was paid here to the reasoning and experiences behind the processing of data and information from the social and behavioral sciences into LCAs. In order to contribute to future enhanced operationalization approaches for behavioral effects it can be considered crucial to understand these matters from a practical and experience-based standpoint. As the climate change related environmental effects of many technologies are intercorrelated with their usage, these effects should also find representation in LCA studies.

Regarding this intercorrelation it is important to address the second research question (RQ2) which can be posed as follows:

- *How are behavior, technology usage and the respectively needed amounts of energy for the technologies‘ operation linked?*

This question inherently correlates with the gathering of knowledge on the social scientific methodological research set up for the investigation of behavior. As the interviewed scientists had expertise in different social scientific subfields and traditions (such as STS, practice theory, environmental sociology, and ethnography), it was of special interest, how the individual perspectives would allow the deduction of different approaches and respective conclusions on interdependencies of the social, technological and environmental spheres.

In order to address these questions related to RQ2, the scientists from the social and behavior sciences were interviewed. Accordingly, particular attention was also paid to the ideas and recommendations that the experts in this field have for quantifying and incorporating behavioral aspects.

With the aim of bringing both – the social scientific knowledge and LCA practitioners' experiences – together to a common understanding, the results of all interviews were put into a comprehensive context. The joint analysis aimed at the identification and understanding of the overarching dynamics of knowledge and data transfer. In order to investigate, analyze and understand socio-ecological interdependencies, skepticism with regard to other research disciplines, acquaintance of knowledge and barriers of knowledge-transfer must be identified. This step was to be taken in the third and final step of the overarching content analysis.

2.2. Context and participants

As a mean of considering the LCA practitioners' experiences and requirements as well as knowledge and insight from behavioral and social science, experts from the respective different research areas were interviewed (comp. Fig. 1). Based on the literature reviews from Tippe et al. [19], and Stermieri et al. [22] LCA studies of smart home technologies were identified. Also, an additional search via Google Scholar, Scopus and Web of Science was conducted in order to identify most recent studies. Concerning the identification of social scientists who did research on smart home technologies also the review from Tippe et al. [19], was used as a starting point to identify potential interview candidates. The contacted LCA practitioners had all conducted LCAs of selected SHTs, which is why they were chosen for the interviews. In order to cover different social scientific perspectives, the experts were selected to cover backgrounds in the STS, ethnography and practice theory. Inclusion and exclusion criteria for a consideration as interview candidate are depicted in Fig. 1. After the identification process based on peer reviewed journal publications research profiles on respective sites (e.g., Researchgate [40], LinkedIn [41], etc.) were screened concerning the experts experience in the field and it was checked if they meet the selections requirements (comp. Fig. 1). In a first round, eight experts were contacted. As not all of them replied

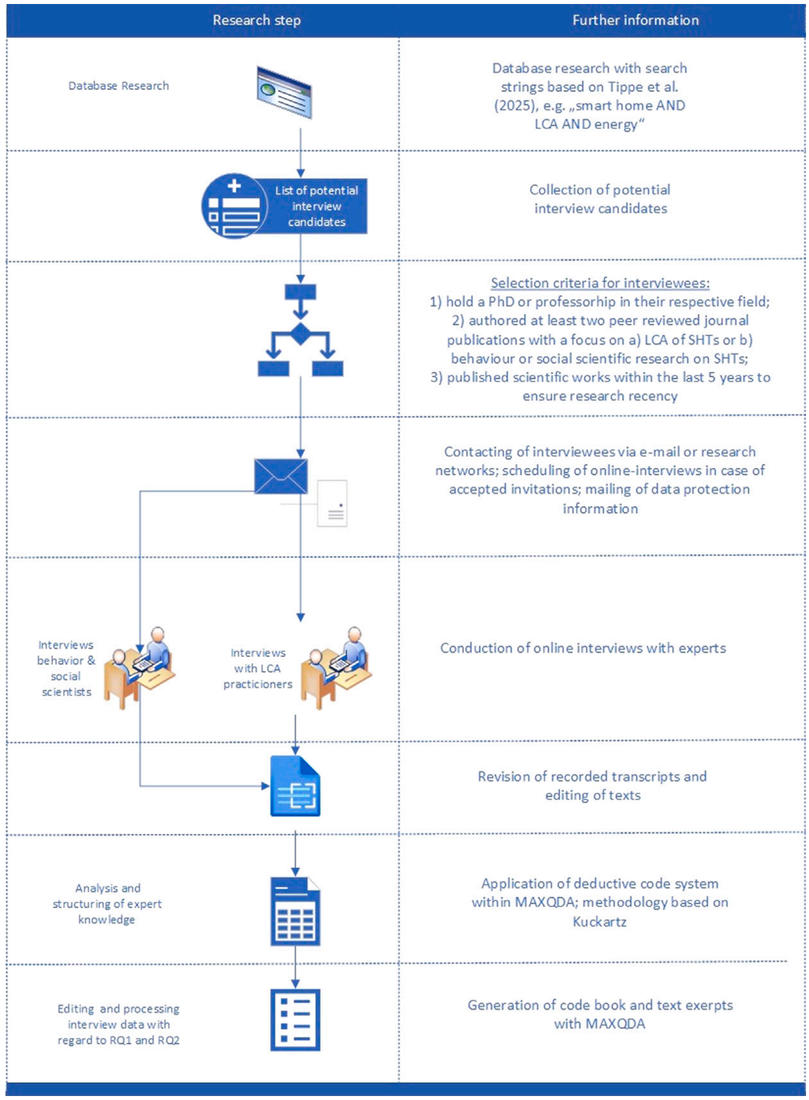

Fig. 1. Applied research methodology: conduction of interviews, followed up by the transcription and content analysis; with regard to the analysis-part, "Kuckartz" refers to Kuckartz and Rädiker [37] and "MAXQDA" to the MAXQDA software [38].

Table 1
Overview of interviewed experts; three of the experts were female, the other five male.

Index	Research field	Research experience	Role	Regional context
LCA_1	LCA & Circular economy	>15 years	University professor	Western Europe
LCA_2	LCA	>5 years	Consultant	Central Europe
LCA_3	LCA (energy research)	>5 years	Researcher (institute)	North America
LCA_4	LCA (energy research)	>10 years	Researcher (institute) & professor	Northern Europe
SOC_1	Anthropology & ethnography	>5 years	Researcher (university)	Northern Europe
SOC_2	STS	>20 years	University professor	Western Europe
SOC_3	STS/Governance	>15 years	University professor	Northern Europe
SOC_4	Sustainability & social sciences	>15 years	Researcher (institute)	Central Europe

or turned down the request, it was reached out in a second round to four further experts. It was aimed for an equal representation of both research fields. The number of interviewees was restricted by the number of potential candidates in general, the reply rate and after the conduction of the last interviews, respectively, by a thematic saturation. If thematic saturation would not have been reached during the coding process of the last interview per field, respectively, an additional attempt would have been undertaken in order to generate more interview material.

In Table 1 a list on the backgrounds and expertise of the participants is provided.

2.3. Data collection

The semi-structured qualitative interviews were conducted based on the methodological advices and approaches introduced by Bogner, Littig & Menz [42]. After the invited experts agreed to the conduction of the interviews, the data protection agreement which is based on the suggested data protection declaration of the University of Bremen was sent to them via mail and video calls were scheduled. All of the experts agreed on the data and privacy protection via mail and/or verbally on the record. Depending on the background of the interview partner one of the two interview guidelines was used (see Table 7 and Table 8 in the Appendix) for the interviews. As the interviews were semi-structured, based on the given answer further inquiries were posed or questions skipped in order to avoid redundant answers. Seven of the interviews were automatically transcribed using the transcript function of the video call software. Due to technical problems during one interview with the expert LCA3, the interview was recorded and transcribed by the author after the interview. To avoid mistakes caused by the transcription function, all of the transcripts were edited by the interviewer by means of listening to the records again and doing revisions where needed. The text base for the applied content analysis was therefore an intelligent verbatim transcript. This format was chosen since no linguistic or phonetic analyses were planned. Instead, the content analysis methodology based on Kuckartz and Rädiker [37] was used for the analysis of the transcripts, and in order to set up the category system, as presented below. As this research is part of a PhD thesis, a single-coder approach was used. In order to prevent confirmation bias and increase the comprehensiveness, though, the code system as well as the code book were discussed and refined with PhD supervisors mentioned in the acknowledgments, whose full access to the interview content was covered by the data protection agreement. Since the transcripts of the interviews could due to their content that includes distinct and recognizable study details allow a correlation to the experts violating their anonymity rights, the full transcripts cannot be published. Declarations, transcripts and recordings were encrypted and are with respect to good scientific practice stored at the IT repository and infrastructure of the German Aerospace Center (DLR) – Institute of Networked Energy Systems. As no particularly sensitive personal data were collected in the research project and focused on expert knowledge, no separate ethics application was submitted. In this regard though, the data protection and processing were conducted in accordance with the principles of good scientific practice of the University of Bremen [43], as well as of the German Helmholtz Gemeinschaft [44]. In cases of legitimate interest anonymized excerpts could be provided upon request, as the data is archived at the scientific IT infrastructure of the German Aerospace Center (DLR) – Institute of Networked Energy Systems.

2.4. Analysis and category system

Based on Kuckartz and Rädiker [37] and [45], the deductive coding approach was chosen to set up the category system used for the coding of the interviews. It is also described as an "apriori categorization" that is mostly independent of the empirical data ([37], p. 72). This means, the analysis and coding of the interviews starts with pre-defined (main-) categories, which were in the here presented study thematically derived from the research questions to be answered. They therefore correlate with the questions posed in the semi-structured guidelines (comp. Table 7, and Table 8). As the apriori approach described by Kuckartz allows a refinement of the subcategories, the final distinctions that allow a sufficient disjunct between the subcategories were formulated during the coding process [45]. During the latter it also became apparent that two further categories (*2.1.2. Objections & doubts* and *5. Other/Context*) needed to be set up for a comprehensive coding of the material, which is further explained in the list of codes in the appendix (Table 6). The predefined categories are presented in Fig. 2. A detailed description of every category and its according sub and sub-sub-categories can be found in the Appendix. As can be taken from Fig. 2, the categories were attributed to the research questions (RQ1 and RQ2) with an intersect in order to account for the interdisciplinary overlap and the interdependencies of the questions. In the following Sections 3.1, 3.2, and 3.3 the results of the coding process are presented.

3. Results

The presentation of the results is structured on the basis of the two main research questions and according to the subtopics addressed within these questions. In the first subsection, a focus is laid on the interviews with the LCA practitioners, whereas the second one presents the results from the interviews with the social scientists. In the third part 3.3, the results are unified into the overarching interdisciplinary context, in order to address the comprehensiveness of the methodological challenges of socio-ecological effects and dependencies. Overall results and overarching findings are then further subsumed and contextualized in the discussion chapter 4.

3.1. RQ1 - Approaches and selection process

In this first part of this chapter, the results from the interviews with the LCA practitioners are presented. After a general introduction, insights on chosen approaches, as well as faced challenges are given.

3.1.1. General insights

In order to understand how LCA practitioners came up with their operationalization approach regarding energy usage in smart home environments, the main category *operationalization in LCA* was set up, allowing the differentiation between the chosen approaches, the reasoning behind it and challenges by means of different subcategories. First of all, though, it was found that all of the LCA practitioners considered the initial steps regarding the data collection for the life cycle inventory (LCI) of the use phase of the SHTs to be challenging. Whilst the ISO norms [12,13] and other guidelines on the general conduction of LCAs were considered to be helpful in many cases, it was also stated that "[...] there is nothing for like the use phase. [...] I don't think there is like a good standard [...] guiding very well" [LCA3]. The selection of operationalization approaches regarding behavioral effects was therefore left to the practitioners themselves. In turn, this led to a variety of different conceptualization attempts, but also a general unsureness about how to proceed.

Looking against this background at the different steps of the LCA (a brief introduction to the LCA methodology can be found in chapter 7.1) - being the goal & scope definition (G&S), life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation — practitioners stated that they were unsure about where to start with the consideration and integration of behavior effects. As it appeared to be rather intuitive to consider the latter within the use phase assessment and therefore primarily in the context of the LCI (where it is also mainly attributed to by the ISO norms [12,13]), one practitioner emphasized the need to factor them also in other parts of the LCA: "But that user behavior or the concept of user behavior already starts with the product choice. So speaking in LCA terms, if we want to address user behavior better in LCA and maybe also compare certain products or certain user behavior styles, it is also important to address the product system in general, and this is something which is quite complicated and not very common" [LCA2]. In the same interview it was emphasized that consumer behavior can also influence the impacts of the end of life of products, as owners can choose to keep, return or dispose them after their usage [ibid.]. This implies, that user behavior also could (and in the practitioner's eyes in fact should) be taken into account within the G&S definition and whilst defining the FU, e.g. by investigating system configurations or technological setups that fulfill specific functions.

3.1.2. Approaches and reasoning

As stated above, practitioners found the operationalization of behavior and the general conceptualization of the use phase within the LCI of SHTs challenging. According to the ISO norms [12,13] the first step of an LCA is the *goal and scope definition* (G&S). Here, the system boundaries, perspectives and the goal of the LCA are set up. They create the basis for the data requirements and collection, affecting the LCI.

First of all it has to be noted that practitioners were aware of the impacts of the use phase: "But basically you want to understand the [environmental] benefit [...] when we talk about smart technologies. You're not creating those benefits in the upstream and you're not creating them in the downstream. So, all the benefits have to be created

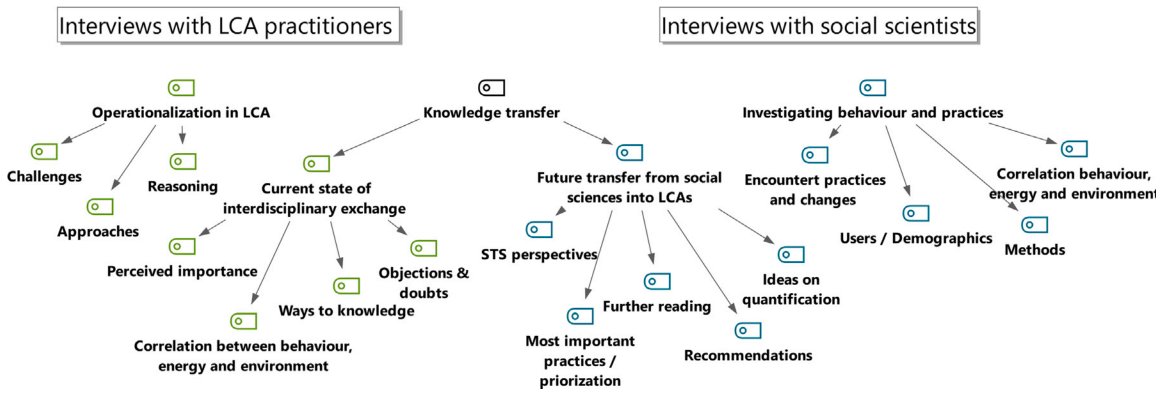

Fig. 2. Graphical representation of deductive codes (created with MAXQDA creative coding [38]): additionally to the here presented codes, in two further main categories the professional background of the experts as well as context/additional information were coded. Codes in green refer to codes used for the interviews that were conducted with LCA practitioners and are therefore mainly associated with the RQ1. The blue codes in return were used for the interviews with the social and behavior scientists, relating primarily to RQ2. Within the main category *knowledge transfer* codes are subsumed that relate to both of the RQs and allow the comprehensive and joint analysis.

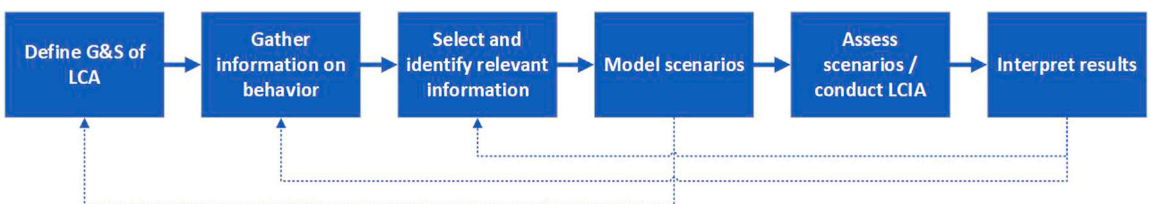

Fig. 3. Derived approach of LCA practitioners to incorporate and process knowledge on behavior. However, it should be noted that the process is less stringent in reality and that there are also iterations, represented exemplarily by the dotted lines. The iterations are possible between every step, though.

during the use phase" [LCA_4]. This can be accounted to be specifically relevant for SHTs and other smart energy technologies providing feedback on energy usage, but shows that there was a general awareness for the anticipated function and ambition of these technologies. Since there are many products which are not designed and produced to benefit the environment, this aim of causing less environmental harm through the behavior or automation-based saving of energy can be considered to be quite unique to SHTs. In consequence, the LCAs there were calculated benchmarks to be reached in order to equal out the EIs caused by the production of the technologies: Practitioners reported against this background that they specifically wanted to focus on identifying environmental benefits of the technologies, therefore, identify e.g. environmental break-even points (the point in time, where the environmental harms caused by the production are equaled out by the benefits caused due to saved energy) or positive effects related to reduced energy usages. This aim led therefore to the assumed cause–effect-relation that the usage of SHTs would reduce the amount of used energy in households.

In order to quantify these effects the most common approach was to model saving scenarios in comparison to a baseline, simulating the energy usage over time of households with input parameters like for example size, number of household members or seasons. In Fig. 3 the commonly reported procedure of incorporating information is presented.

During the course of the interviews it became apparent, that it can be described as partially coincidental, which theories and findings made it into the energy usage scenarios: "I just read a lot of papers. That is what I have done. [...] I was just trying to understand what my [...] advisor told me [...]. Then I got no guidance after that. [...] So, I just started reading papers on like different stuff" [LCA_3]. The interviewee LCA_4 reported of a similar experience: "No, I mean... I'm not a social scientist, so you know it's always when you work in multidisciplinary issues when you are touching a topic that is not really yours, you are not so comfortable in what to choose, what not to choose. So, [...] it [anot.: the chosen modeling approach] was maybe the one that was the most appealing". It was also added, though, that "[...] there are not so many publications not so many studies that go into this kind of details. So, in the end, if you have to be kind of in front of the science, you also have to come up with your own methods and then they might become validated in the future or they might become invalidated and say that what was the wrong approach" [LCA_4]. That the chosen approach could turn out as (in-)valid, was here therefore faced with an attitude that can be considered pragmatic. One of the biggest challenges next to the lack of guidance reported here for the practitioners was the lack of 'real life' data. The decisive factor for setting up the scenarios therefore appeared to be the plausibility and manageability of insights to and by the practitioners. Once they had a basic idea of the technology usage based on literature and in some cases talks with colleagues/peers, they started modeling the energy usage scenarios e.g. in Matlab or other software environments.

In view of this it was of special interest what the reasoning behind the choice of the approach was. This reasoning can be described as a conflict between data availability, pragmatism and available resources (e.g. time, financing or knowledge). The lack of data led to different ways of trying to close these knowledge gaps: whilst literature was one approach ("We couldn't really study [...] how people would react to the smart home, the smart energy management. So, we had to use whatever literature we could find". [LCA_3]), others conducted surveys themselves [LCA_1] or hired a company to gather panel data [LCA_2]. Also, a project context could be a limiting factor: "I had no choice in the matter. As I said, I was I latched onto existing initiatives and projects" [LCA_1]; here, data availability and methodology were already a given by the circumstances.

3.1.3. Challenges

Even though some of the challenges relating to data processing in LCAs have been partially disclosed in the previous chapter, specific challenges will be made explicit as follows. In general the challenges can be divided into *individual* and circumstance-rooted, so *external* ones. Concerning the latter, faced obstacles were most often a lack of resources. Practitioners found themselves for example employed in research projects or PhD positions, granting them a limited amount of time and sometimes also financial resources for themselves or within the projects [LCA_1-LCA_4]. These circumstances could leave them with few or no opportunities to gather own data, necessary to actually fit the scope of their LCA [LCA_3, LCA_4]. As they might have found themselves as the only ones working on the LCA of the SHTs, there were not enough resources for 'deep dives' into other research fields. Relying therefore on literature, they faced the challenge of only finding data that did not necessarily fit their own research scope or informational needs [ibid.]. This in turn made it necessary to adapt data types and information (e.g. narratives on rebound effects or theoretical models) in contexts they were not gathered or set up for. This does not account for all the LCAs on SHTs and energy management systems, as in two cases [LCA_1, LCA_2] practitioners actually were able to set up own surveys. The opportunity to do so cannot be taken as given, though.

A further external factor relates mainly to the (research) environment the practitioners found themselves in: here, two of them reported about research peers who regarded interdisciplinary ideas and approaches as unavailing or had a negative attitude towards them: "If you are an engineer, you are in a lab with other engineers or the professors are engineers, [...] and you start talking about social psychology, [...] it takes a lot of education. So that is kind of what I faced and I succeeded at the end [...], I got people on board, to some extend. But I was still the only one doing this sort of things" [LCA_3]. Also, the expert LCA_4 described 'leaving' the former research field as "a lonely process".

Individual challenges in comparison to the external ones refer particularly to those that are caused by e.g. the academic backgrounds of the practitioners, but of course also personal experiences and attitudes. A reoccurring topic when it came to knowledge access was a feeling of not knowing where to start or how to proceed: "I'm not a social scientist. So, for me, it was a bit complicated to delve into this. And that's why I decided, [...] let's just split them [annot.: the users] into [...] [groups] and then it doesn't matter who they are" [LCA_4], explaining the process of uncoupling 'energy consumption scenarios' from the actual technology usage and behavior of people. Here, it becomes a matter of how comfortable and especially confident the practitioner feels with leaving his or her primary research field. Against this background, expert LCA_4 also emphasized how specific this type of interdisciplinary knowledge is: "I didn't know many social scientists at that time, especially focusing on this consumer behavior in the energy domain. So it's kind of quite specific to find a person that is in that domain". Interdisciplinary knowledge on energy and technology usage was therefore regarded as hard to access and only via (in this case not yet existing) scientific networks and communities.

In Fig. 4, the influence of internal and external factors influencing the behavior operationalization is pictured.

One additional challenge not depicted in the figure is one that can be considered external, but does not relate to the research environment, but the LCA methodology itself: "My advisor was an anthropologist. Which is great, he knows a lot about how humans behave, and culture, but it's not quantitative. And for my modeling I needed quantitative data" [LCA_4]. Summarizing, it can be stated at this point that there was a feeling of doubtfulness (especially concerning the usefulness of social scientific data for the quantification led methodology of LCA), combined with an impeded access to specific knowledge. This lead to the circumstance that although attempts were made to counter the complexity of the system by using scenarios and complex mathematical approaches, the coupling of modeled energy consumption with actual human behavior and its underlying social backgrounds remained difficult.

3.2. RQ2 - Bridging disciplinary gaps

In this chapter the results from the interviews with experts from the behavior and social sciences are presented in relation to RQ2.

3.2.1. Investigating behavior

In the first part of this subchapter the methodological approaches mentioned and discussed by the social scientists are introduced. In the second part, insights considered to be most relevant by the experts are described. Concerning the methods that were used to investigate the behavior of people living in smart homes a broad variety of qualitative and quantitative approaches was found. As the researchers had professional backgrounds in different social scientific schools and disciplines, this had also an impact on their respective field access, next to the research questions that had to be addressed.

When it comes to quantitative methods, surveys – under certain circumstances combined with qualitative pre-surveys – were the preferred method. They were not always conducted by the researchers themselves, though, but would also be executed by an agency. The reason for the methodological choice was explained for example like this: "it's just because we liked to quantify the phenomenon of usage of smart energy services" [SOC_4]. The same researcher elaborated also the advantages and downsides of the methods: "The weakness [...] is just that you cannot dive as deep as you would like to [...] into a topic or some issues that you did not explore well. So, it is not flexible to elaborate new reasons or whatever is on the head of people, but the strength is the quantification of phenomena and relationships" [ibid.].

The weakness of not being able to 'dive deeper' into the underlying circumstances of the investigated behavior on the other hand was addressed by qualitative methodologies. The latter can in comparison provide more exploratory and explanatory results. Being interviews, focus groups, (co-creation) workshop, site visits, (photo) diaries and home tours that were conducted by the researchers, they covered a broad spectrum of 'classic' social scientific but also ethnographic research methods. One of the researchers argued especially for the usage of ethnographic methods, as "[y]ou can do a lot of interviews in a relatively short amount of time and get a lot of information but then [...] you trade that for some depth in those households" [SOC_3]. Expert SOC_3 reported also that in his view rich qualitative data can and should be used in order to put calculated technological potentials (e.g. energy saving potentials) into a more 'realistic' context. In his experience, potentials and impacts of technological solutions are often estimated too high and would not account for the social dimension. Here, he argued, the collection and implementation of qualitative data could help to come up with more 'realistic' estimations and prevent exaggerated promises.

A common ground between all the interviewed experts was the notion that qualitative research methods can create a deeper understanding of the investigated phenomenon, whereas quantitative methods provide a bigger or more 'representative' picture. For the purpose of generating a more comprehensive overview of the researchers statements and experiences, they were collected in Table 2.

As can be taken from Table 2, the methods used by the researchers to address different research matters allowed the deduction of potential contributions within LCA studies.

So far mainly potentials and experiences have been discussed, but researchers have also been questioned about challenges they see when it comes to the implementation of social scientific methods into LCA studies. One of these challenges mentioned independently of the methodology chosen by the scientists was the investigation of long-term effects of energy usage in the light of the 'smartification' of households. As many research projects do not run long enough to investigate effects occurring after a maximum of – if at all – a couple of months, impacts and influences of energy technologies on peoples' lives over longer periods of time cannot be sufficiently investigated. The

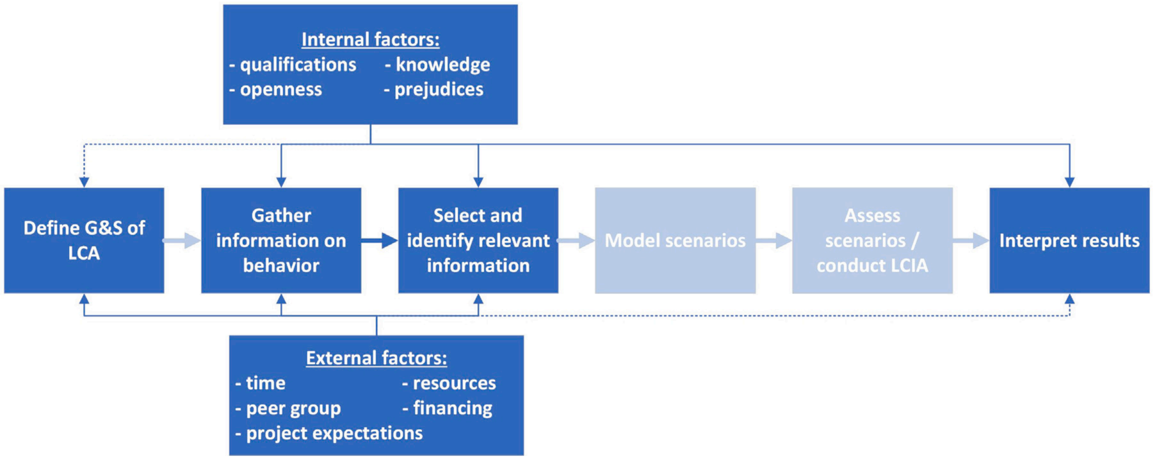

Fig. 4. Modified version of Fig. 3, depicting internal and external factors influencing the behavior operationalization approach in LCAs of SHTs. The dotted lines represent a weaker influence on the respective steps, whereas the continuous line depicts a stronger impact.

Table 2
Method overview and recommendations.

Mentioned methods	Perspectives/explanation	General potentials for LCA
Structured/unstructured/semi-structured interviews [SOC_1, SOC_2, SOC_3]	gather first hands experiences; very diverse interview formats allow adaption to different research contexts; adjustable in depth and focus	understand technological setups; inquire how people adjust to certain technologies
Focus groups [SOC_3]	inquire and discuss different perspectives at once; support in decision making	incorporate different views and opinions in decision making contexts; set up story lines or scenarios
(Co-creation) workshops [SOC_3]	allow 'action-oriented interventions'; incorporate (user) needs directly into technology development	influence decision making in design and development processes
Site visits/home tours/show and tell tours [SOC_1; SOC_2]	gain insights on household dynamics; understand and explore 'digital agency'; - focus on human and non-human interaction; less 'decontextualized' than an interview	understand the context of EIs caused by certain practices; comprehend and interpret the (un-)changeability of practices
(Photo) diaries [SOC_1]	ethnographic method, if on-sites are not possible; gain deeper understanding of technologies meaning	understand the implementation of technologies and the role of energy in every day contexts
Quantitative surveys [SOC_2; SOC_4]	gather information on the frequency and commonness of specific behaviors; cover representative and large user groups	enable clustering and mapping methods; allow conclusions on the frequencies of system setups or statistics with regard to the occurrence of behaviors

long-term perspective is therefore apparently a challenge, especially caused by the external circumstance of research funding.

With this in mind, however, the researchers were also asked what their most important findings were in general with regard to the use of SHTs. The researcher SOC_2 recommended not to equate the intended use and purchase intention with actual effects. Just because someone has the intention to use a smart meter to save energy, for example, this does not mean that the purchase will actually have this effect. Also SOC_1 emphasized the meaning of routines and habits, especially in household contexts, even though some might be more easy to change than others: "I think if you look in the home and household practices, I definitely think cooking is a place where people are less flexible" [SOC_1]. One conception that one of the researchers warned against was that in the future automation would take over all problems relating to flexibility and load shifting. In his [SOC_3] experience, this 'automation turn' initially sounded like a promising approach for many engineers in order to 'take humans out of the equation as compromising factor' and thus generate more reliable data. However, from his perspective developers and therefore also people who are assessing technologies need to be aware that there are people who would not even allow any kinds of automation in their household. In addition, these systems – if installed – could also be overridden, meaning that even in the case of energy usage automation, a 'correct' use cannot be assumed by default [ibid.].

The last aspect to be addressed in this chapter is the selection of test persons taking part in the scientific investigations. This selection can obviously highly influence research results, which is what makes it so crucial for all different kinds of research (comp. [46]). A common ground between the experts was the understanding that within test groups ideally diverse sociodemographic backgrounds should be covered. It was, however, self-explaining that the selection of a test group is also closely linked to the research question addressed. While recruiting test groups it cannot always be influenced by the researchers who the people are responding to their calls, though. Against this background, expert SOC_1 reported for example of regretting to not putting more effort into identifying female participants and recruiting people living in non-hetero-normative households: "So I would have been more proactive on that if I knew that topic [annot.: gendered household practices in smart homes] would be my main concern before". She and also two other experts mentioned the impacts of SHTs on gender-related household practices, which leads to the conclusion that especially in research on energy technologies introduced in households diverse test groups should be considered.

Whilst the experts reported technology-influenced practices that could be associated with aspects of age or gender, they warned against the drawing of conclusions that bring sociodemographic factors into a cause–effect-correlation with specific practices or behaviors [SOC_1-SOC_3] ("I'm quite sort of skeptical of the kind of sociodemographic kind of argument. I think probably what's [. . .] more important is kind of people's sort of personal backgrounds and histories really. [. . .] if there were two kind of sociodemographic dimensions that have come out that are often important, but not always, they would be age and gender. And in both cases, I think it's sort of almost by virtue of social practices rather than by virtue of demographics" [LCA_2]). Here, the recommendation was – particularly against the background of operationalizing behavioral effects – in comparison to the latter approach, to choose an approach focusing on shared lifestyles, habits or practices. This could for example be realized my means of using clustering techniques. This way would – in the experts' view – also allow a differentiation that could be for instance based on user preferences like choosing a more behavioristic approach on saving energy (e.g. changing energy using habits solely based on feedback tools) or preferring technology-/automation-based strategies. Rather than connecting use related EIs with sociodemographic factors, this strategy could lead to more conclusive results and allow decisive interpretations.

3.2.2. Operationalization and contextualization

Prior to the request for recommendations, the social scientists were asked if they are familiar with LCAs, in order to make sure they have a general understanding of the assessment methodology. In one case a brief introduction had to be given, the other experts were familiar with it. Concerning the conceptualization of user behavior all of the experts argued for an approach that uses data sets based on studies instead of theory-based models. They mitigated especially against the mathematization of theoretical approaches like the theory of planned behavior [47] or other decisions/behavior models, in order to explain and operationalize behavior for the use phase ("I would really go for the empirical side. This makes it easier for you to prevent from superficial and saves you from a lot of questions why you proceeded as you proceeded. And you would have to defend the theory you've chosen, for example, theory of planned behavior - it's not everyone's darling. It's a very trivial theory actually. So, I would go for the empirical approach. And having said that, it also has a slight difference like with the empirical approach you're about to assess – how many do that? What kind of typology is there?" [SOC_4]). Rather, it was suggested, actual inquiries and measurements should be used to set up different forms of use cases and scenarios.

Researcher SOC_3 spoke out in favor of a differentiated but more 'relaxed' approach to data in modeling. He emphasized the discomfort that many social scientists have in reducing complexity, but also argued that this discomfort should be at least partially discarded in the context of modeling ("[...] I think this discomfort comes from the 'okay so we know that everything is super complex and we gather this fantastic information about all sorts of interdependencies and links and multiplicities and complexities [...]. But. . . !' Those people [...] who make models and who make classical assessments – they can do nothing with this complexity, right? So, it's, so I think we should be really really kind of think that it's not violence on the, you know rich social reality to kind of. . . reduce the complexity sometimes in order to make some stylistic and simple points in a model I think. That is really not the case. We know that those models have tremendous political force and impact. They will be worse without [...] simplifications. And they will never be able to sort of take up the complexity of the social world that we think it deserves." [SOC_3]). On the other hand, he called on to refrain from excusing over-simplification of issues on the behalf that they are complex. At this point, he pointed out that one "can do better than to say 'it's complex'" [ibid.]. Here, therefore, a call for an enhanced balance between simplifications and accounting for complexity can be deduced.

Another suggested approach aimed at the parallel use of qualitative and quantitative data originating from the same or at least a similar context. In other words, this means using mixed research methods in order to gain a deeper understanding of the technology usage itself but also of the 'bigger picture' of circumstances and the surrounding (home) environment. This, the researchers argued, would not only allow more reliable conclusions on the actual usage of energy technologies, but consequently also provide more validity and depth to the assessment of environmental effects ("So, I'm thinking about how then this kind of combination of theory and identification of different, if they are social groups or you know practice clusters, lifestyles, you know whatever they may be or you call them, so this combination of a theoretical understanding of change and empirical identification of certain traits will probably then inform what you think when you want to introduce some sort of intervention and also kind of how it will effect life cycle and I guess in terms of emissions and whatnot" [SOC_3]). Next to the development of scenarios and their according incorporation into the LCIs of LCAs, it was emphasized that especially the interpretation of the environmental effects caused by technologies would benefit from a deeper understanding of their usage. The actual link between impacts on the environment and the respective human behaviors causing or relating to them could in this way be understood on an enhanced level ("But some of these insights that we have on the variation in terms of how people use it and some calculations of the scenarios. [...] so that could add these nuances and show this complexity" [SOC_1]). Based on these statements and results, it can at this point be concluded that socio-ecological interdependencies in particular could be better comprehended in this way. In addition, implications or recommendations derived from LCA results and interpretations would be expanded to the inclusion of the dimension of human behavior and thus become more meaningful.

3.3. Transferring and transforming knowledge

In the chapters 3.1 and 3.2 the interview results were presented separately according to the professional background of the experts. In this last result chapter, though, they are contrasted against each other in order to illustrate reciprocal reservations against the other respective research disciplines, but also to present chances for an enhanced interdisciplinary exchange of knowledge and exchange. Before individual aspects are further discussed below, in Table 3 the insights from the interviews are contrasted against each other.

All interviewees reported a recognition for the value and importance of the respective other scientific discipline(s). Nevertheless, some reservations about the other disciplines could be identified in most of the interviews. LCA practitioners emphasized the need for reliable, quantitative data, suitable for model inputs. They experienced not only a lack of understanding from their peers but also had biases against qualitative research ("And for my modeling I needed quantitative data. Typically like, directions and things, but I would miss the quantitative aspects". [LCA_3]). In comparison, experts from the social sciences criticized on a rather general level that in their view natural scientist and engineers would most often not account for the human dimension of technology development and assessments. They did not impute that any of them had bad intentions when it came to the development of new technologies. However, they accused them of not taking sufficient account of the dimension of 'people and their needs'. Based on these findings and statements, an overarching – but often rather implicitly communicated – field of conflict could be identified which is the handling of uncertainties and complexity in the different research fields.

As a final and overarching result, an overview of possible integration options for social science methods and findings from the behavioral sciences will be presented at this point. In the overarching analysis, it became clear that social science and ethnographic methods can potentially lead to an improvement in the LCA results, but that the areas of application and types of results can vary greatly. A distinction must be made as to whether these social scientific methods are used directly for operationalization and quantification or are primarily contextualizing in nature.

Table 3
Contrasting juxtaposition of positions expressed by LCA and social science experts.

Topic	LCA practitioners	Social Scientists
Identified approaches	ABM, theoretical models, literature, surveys	Home tours, (photo) diaries, interviews, focus groups, surveys
Challenges	Lack of resources (time, financing, knowledge); reducing but representing complexity; quantification of behavioral effects; peer-pressure	Assessing long term effects of technology implementation; accounting for complexity whilst reducing it; overcoming disciplinary boundaries
Requirements/Recommendation	Compatibility with ISO-norms; hands-on approach (guidance on test group and method selection, advice on documentation); applicable to a variety of contexts	Choose between or combine contextualizing (qualitative) and operationalizing (e.g. clustering/statistical) methods; mixed-method approaches rated most fitting; accepting losses of complexity whilst creating awareness for it

It turned out that quantitative surveys or interviews were considered to be particularly suitable for the actual quantification of behavioral aspects. As these can be statistically analyzed but are not based on purely theoretical considerations, they could be used primarily to decide on the setup of the systems under consideration. They could also be suitable for defining system boundaries. If the usage of technology is to be mathematized, clustering and mapping methods based on questionnaires were discussed. Practices that are interwoven with the use of energy and are influenced by technologies such as SHTs could be systematized in this way.

In addition to these methods, which could be used directly for operationalization, qualitative approaches for interpreting and contextualizing results were discussed in the interviews. These were primarily approaches from the STS, which shed light on the general interactions between technology development, utilization, users and designers ("We need to look at specific cases in particular places. And explore what happens. So that immediately leads you down the route of more kind of participatory, more ethnographic, more kind of interview-based methods and more interpretive kind of informative analysis. It militates against the big survey or something like that" [SOC_2]). With a view to LCAs as a support tool in decision-making processes, these could provide far-reaching insights, especially for the G&S and interpretation phases.

What therefore became apparent was that the different methods, each with their own knowledge potential, can contribute differently to an LCA. It is also important to acknowledge the diverse scopes an LCA can have, when selecting social scientific methods as tool in the respective study. In the case of energy technologies, for example, a distinction can be made as to whether it is a single technology (e.g. a smart meter or a photovoltaic panel), or whether residential neighborhoods, regions or entire energy systems are being considered.

What became clear in the interviews, however, was that social science and ethnographic methods can contribute to improving the validity of the LCA results, both in providing context to results as well as direct approach for the quantification and operationalization of behavior ("And I think then it would also be easier to actually incorporate also qualitative perspectives into the quantifications because then…I mean, you would have the numbers but you can could still way more easily contextualize them with qualitative data that you started with or came up with beforehand". [SOC_3]).

4. Discussion: Quantifying the unquantifiable?

In this discussion the results presented above are contrasted against each other and against the current state of research practice. Also, identified barriers for knowledge transfer are summarized in the first part 4.1. In the second part the implications deduced from the interviews are contrasted against the ISO norms 4.2. In the closing subchapter 4.3, limitations of this study as well as future research implications are presented and discussed.

4.1. Subsumption

Firstly, the insights gathered from the interviews are contrasted against each other, followed by a comparison to the state of the art of research in the next chapter 4.2. A topic that was beside the aspects mentioned most often in the interviews and discussed controversially, was the one of representation and the handling of socio-demographics. Whereas it was argued by the social scientists that it is more important to have diverse test groups in order to gain insights on different (technology) user types and to be potentially able to map them, for the LCA practitioners the aspect of statistical relevance and representativeness were perceived as being more important. The clustering methods mentioned above could offer an attempt to combine these two perspectives. These methods offer the possibility of depicting different user types, but also of providing them with statistical data and thus making them more applicable within an LCA. Even though there was a strong understanding for the necessity of quantification in the environmental sciences, models should in the eyes of social scientists not be based mainly on theories, but on actual data gathered on energy and technology usage and the respective behaviors and habits relating to them. Also, it was argued, if only the energy usage pattern itself is regarded, it does not matter who the users are and which behaviors lead to this specific form of use. As this might be less relevant for the total EI, it should be considered important for the interpretation and when policy recommendations are derived from LCA results. Against this background SHTs provided an interesting use case, as household practices and related energy usages are highly individual and therefore also go along with different EIs. Summarizing the perspectives of the social scientists in this regard, there is also a strong need for the accounting and coupling of qualitative data with LCA results. Although mixed-method approaches are already quite common in other research fields, they are still rarely found in the context of LCA studies. It has to be differentiated though, if social scientific methods are used for the operationalization process itself or for a broader contextualization of LCA results. This will be further discussed in chapter 4.2. In general it has to be stated that as there was a lack of various resources for a detailed examination of the topic, simplifications were often the way to be able to take behavioral aspects into account at all. To summarize the above-mentioned points and in order to give a comprehensive overview of expressed doubts and ideas derived from the interviews to overcome them, in Table 4.

The suggestions derived from the interpretation of the interview content emphasize the need for improved guidance on the alignment of the LCA methodology with social scientific research approaches. Nevertheless, they also demonstrate potentials for a variety of applications and possible contributions. Whereas the discussion above focuses mainly on the enhancement of existing social scientific methods, there was also a development need identified concerning those methods themselves. The assessment and investigation of long-term perspectives needed for the execution of (prospective) LCAs, needs an adaption of the social scientific methods of the investigation of extended time

Table 4
Alignment of expressed concerns and options to overcome them.

Expressed concern	Key suggestions for LCA practice
Validity of small test groups	Small test groups might not meet statistical measures of representativeness; they can though provide qualitative insights on actual usage, provide feedback and can through personal contact be more easily involved in co-design approaches and stakeholder processes.
Validity of qualitative research	Qualitative research helps to understand intentions, practices and habits of users; narratives and qualitative data can be used for contextualizing LCA results and/or for generating use scenarios.
Transferability of qualitative and ethnographic insights	Ethnographic methods like occupancy or use diaries can offer explicit insights into the usage of technological devices. More guidance on study setups and analysis for LCA contexts is needed though.
Need for quantitative data sets	The social sciences offer a variety of statistical approaches (surveys, questionnaires, cluster analysis etc.) that promise an applicability to diverse questions faced in LCA use phase modeling (e.g. usage time, expected and actual useful life of product, allocation of practices to different user clusters, …).
High costs of surveys	The possible necessity of social scientific data as input for LCAs could be considered whenever there is an application for research funding and grants. The importance of the data should be communicated so that e.g. funding agencies can provide third-party funding for it.
Access to social scientific knowledge	Aiming for a greater cooperation between the disciplines could improve the validity of the integration of social scientific knowledge. Also, aiming for interdisciplinarity within research teams could improve the exchange.
Accounting for long-term effects	LCAs in many cases cover broader time horizons and frames or aim at doing so. This first of all has to be met with methodological improvements for extrapolations on the social scientific side. For now, though, e.g. scenario building coupled with uncertainty analysis could be one way to address this challenge.
Use of theoretical models from behavior science and social psychology	It was argued against the application of theoretical models used for behavior modeling. Instead, measurement or survey data should be used for scenario creation in LCAs.

periods. As was shown in chapter 3.1.3 a greater awareness for actual possibilities of operationalization approaches has to be generated in norms and LCA guidelines. Needs regarding the quantifiability of behavioral effects have to be met by (new) social scientific methods, balancing necessary simplifications and an accounting for the complexity of human interactions with the invisible resource of energy. Only if options for an enhanced operationalization are communicated and practitioners can find information on the relevance of behavior is there a chance for a broader establishment of new approaches.

4.2. Implications and comparison to the state of the art

To the knowledge of the author, there are up to date no general guidelines or even just well established methodological approaches for operationalizing behavioral effects in LCAs of energy technologies or in general. Di Polizzi Sorrentino et al. [23] suggested the integration of different social scientific methods, but provided a very broad range of options without a focus on (energy) technologies. Stermieri et al. [22], on the other hand, introduced a taxonomy for the integration of user-related effects in LCAs of energy using technologies based on the review of studies on different ICT. They differentiated between *direct*, *indirect*, *rebound* and *systemic impacts on technology and society* concerning the impact of behavior on the energy usage, correlating them with different user behaviors (micro-level effects: *usage effects, substitution effects, changed practice effects, time rebound effects, and induction rebound effects*; macro-level effects cover *space effects, transformational effects, learning effects, and spending effects* (p.2f)). Their analysis showed that "[a]lthough the variety of users' effects is known in the literature, and it is recognized that increasing the number of effects analyzed increases the quality of the results ([48] [source adopted from original quote]), none of the studies analyze all of them together" (p.15). This goes along with the finding from Tippe et al. [19] that revealed a strong focus on rebound effects and the consideration of practice changes in LCAs of SHTs. Both reviews show, though, that regardless from if direct, indirect, rebound or system effects concerning energy usage are addressed, both, the choice of methodological approaches as well as the selection of regarded user effects (e.g. practice change, induction etc.) are highly dependent on the LCA practitioner's choice. Whereas reviews provide insights on research outcomes, the here presented study gives to our knowledge for the first time insights on the actual research process that may lead to this diversity of approaches and also the underlying challenges that practitioners face. It can therefore be considered as a gaze into the black box of the decision and conceptualization processes that takes place prior to a published LCA and the actual scientific practices. This current study in contrast to reviews identified challenges first hand from practitioners and put them into one interdisciplinary context with social scientific perspectives. The here presented results relate especially to what is introduced as the assessment of practice/behavior induced changes and their impacts on energy usage by Stermieri et al. [22]. As their review suggests, tough, could the lack of comprehensive methodological approaches reported by LCA practitioners also result in the problem of the incomplete and fragmented inclusion of effects caused by user behavior they identified.

This as well as the interviews show the need for an elaborated framework, as also discussed further below. As the focus of this work was identifying challenges and chances of and for behavior integration in LCAs, a complete and comprehensive framework will be introduced in future work. In order to deduce implications for the LCA practice based on the interviews already, though, in Figs. 5–7 the recommendations and insights were conceptualized and assigned to the LCA steps introduced in the ISO norms [12,13].

The three Figs. 5–7 provide an overview of possible steps of integrate and consider the recommendations of the social scientists with respect to the four steps of an LCA. The arrows in the middle of the depictions thereby symbolize the underlying iterative conception of the LCA methodology. In order to give an overview of possible insights providable by the three different concept and approaches provided above, some possible insights were deduced for a fictional case study of a thermostat in Fig. 8. In reference to Stermieri et al. [22], this would affect especially the investigation and consideration of micro-level effects.

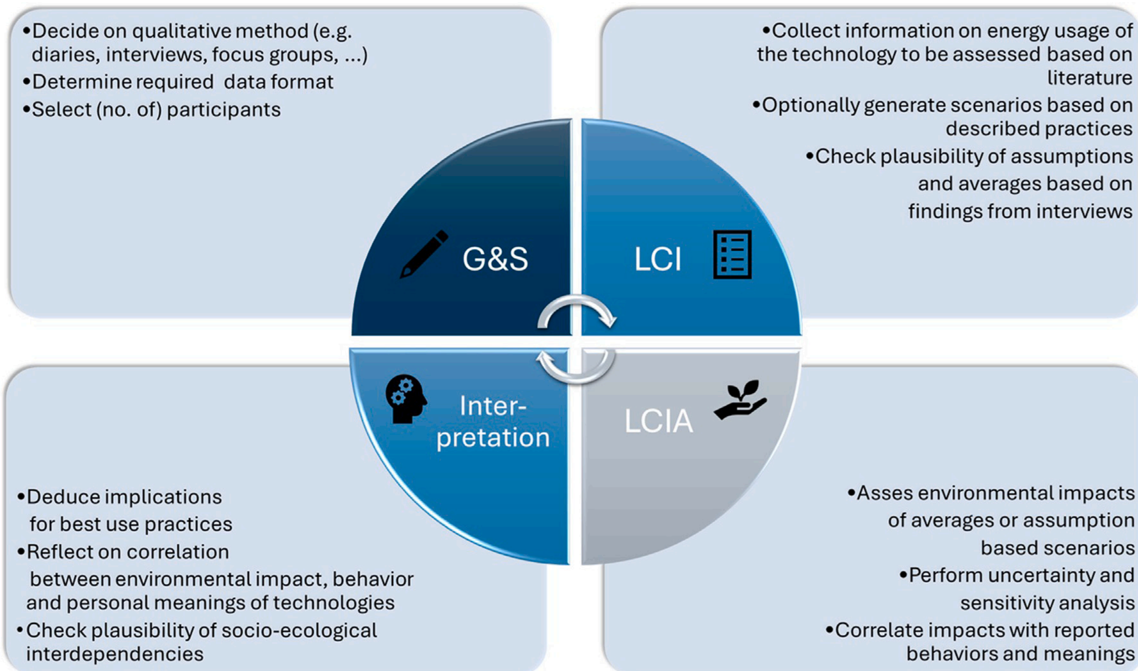

Fig. 5. Adapted ideas and implications for the consideration of behavioral effects in LCAs, using qualitative methods in order to provide context and background knowledge to the EIs of assessed technologies.

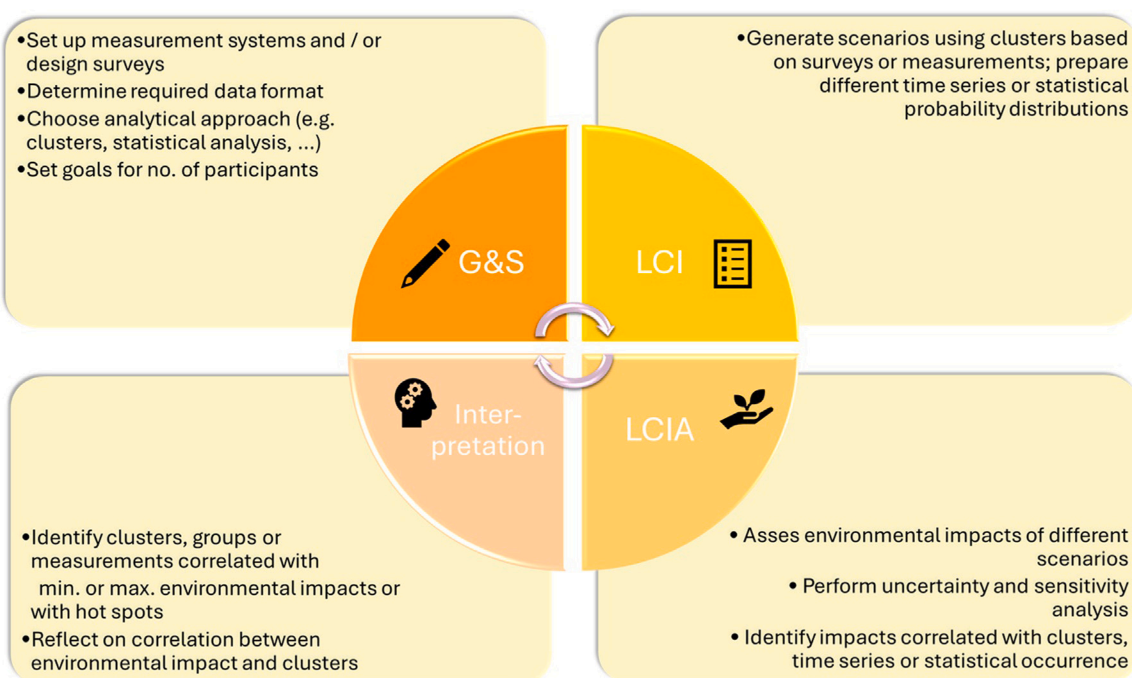

Fig. 6. Adapted ideas and implications for the consideration of behavioral effects in LCAs, using quantitative methods in order to operationalize behavioral effects and related EIs.

It is depicted in the figures that both recommended methodological strands, so contextualization as well as operationalization can contribute to setting up scenarios for use cases. For the contextualization approach, though, this step is rather limited to evaluating assumption and/or to generate use cases based on reported behaviors.

Direct resource usage measurements recorded e.g. by smart meters/smart plugs and quantitative approaches can directly provide for example time series of usages, data on use frequency etc.; the qualitative methods in this case need a further processing step, translating narratives, diaries or reported behaviors into plausible scenarios. This could though be a promising approach for assessments without resources for extensive measurement or survey campaigns. Again in reference to Stermieri et al. [22], the qualitative methods would also in the first place allow insights on which of the micro-level effects are occurring during technology usage and the users adaption to new technologies.

In cases where only data on average uses or rough estimations are available, qualitative methods could also be used as background

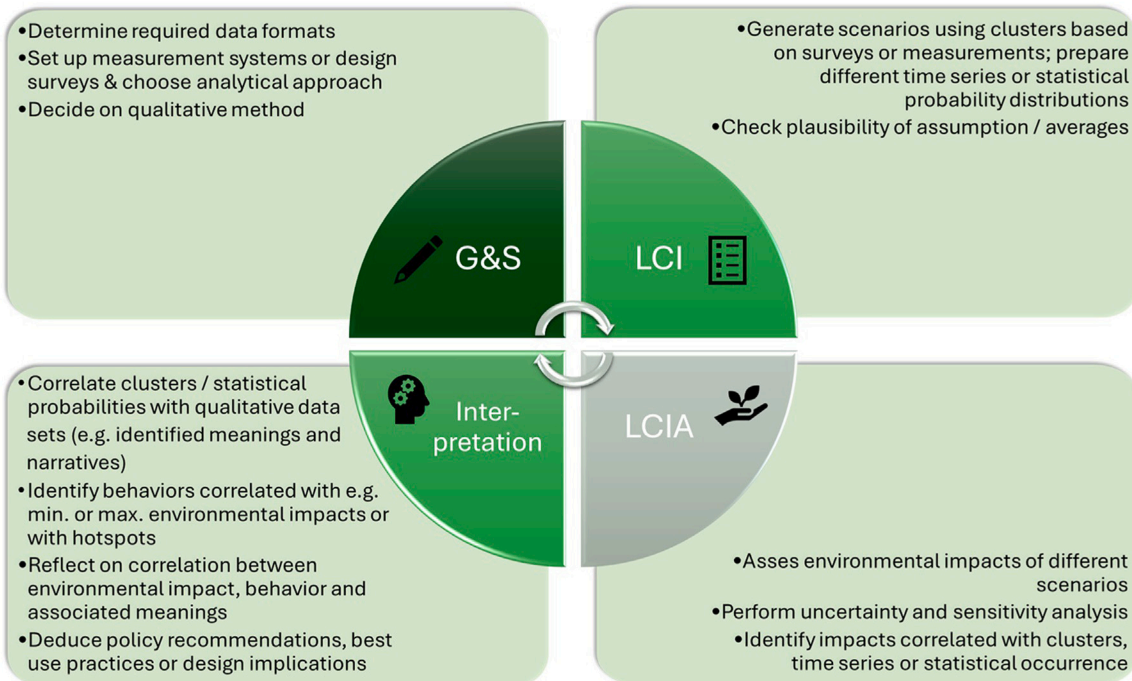

Fig. 7. Adapted ideas and implications for a mixed-method approach, considering of behavioral effects in LCAs for operationalizing, understanding and assessing their correlation with EIs.

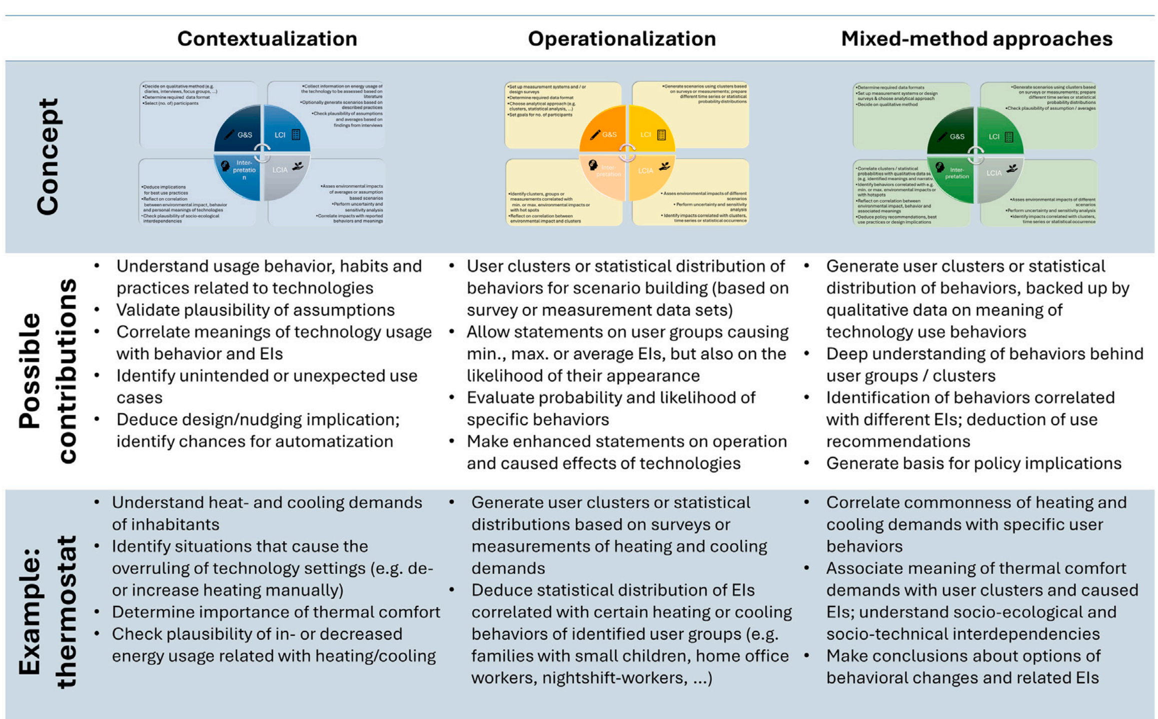

Fig. 8. Suggestions and deduced benefits of the different methodological approaches to consider behavioral effects in LCAs; presentation of ideas for an examplary LCA case study of a ('smart') thermostat.

knowledge to make plausible choices for scenario setups. In the case of average, they could also allow estimations on diverging technology usages and according energy consumptions. They could also offer an option to estimate if scenarios on in- or decreases of energy consumption related to specific induction or nudging intentions can be considered realistic.

Discussed and suggested methods for the operationalization could especially be used for generating usage scenarios in the first place. This could for example include the execution and analysis of survey data, leading to a statistically based parametrization of user effects. Also, clustering approaches that identify and systemize user clusters (like for example performed in [49] for the case of water usage). With regard to documentation and also emphasizing the importance of behavioral effects, software used for the performance of LCAs (like SimaPro [50], OpenLCA [51] or Brightway2 [52]) could provide optional task bars or documentation files, which on the one hand emphasize the need for the consideration of user behavior and on the other hand directly provide resources for scenario building.

4.3. Limitations and future research

In this section limitations of the here presented work are discussed and implications for further research are presented. In this study the focus was laid on the assessment of SHTs, making a broadening of the scope necessary in the future in order to improve the generalizability of the found implications. The chosen scope limits the transferability and possibilities as in the case of SHTs a strong relation between the usage of the products and the related energy usage is expectable. As there are many products that are generally independent of an energy supply in the fulfillment of their intended use, a stronger specification of products, where the use phase is specifically crucial concerning their EIs should be made. What is meant here, is that for example, consumable goods like cosmetics and food as well as furniture that is prone to wearing and tearing will of course have significantly other use phase impacts than electronic devices and SHTs. Therefore, a specific definition is to be set up for which technologies an elaborated behavior operationalization is useful and necessary.

This notion, nevertheless, also underlines arguments brought up concerning the functionality dependency of products/technologies suggesting to refrain from assumption based use phase models. This does not only include the question which purpose the investigated technology is supposed to fulfill, but subsequently, in which ways users are actually adapting to the technology, going along with the specific, individual energy usage. Some of the above practices (e.g. heating, cooking, leisure activities, child care) and behaviors relate strongly to home settings and home making. A general framework for behavior contextualization and operationalization would need to be tested in a variety of context in order to ensure a broad applicability. In industry or mobility cases, this would first of all include steps of a clear user definitions based on responsibilities (‘whose behavior impacts how a technology is used?’ or ‘who uses a specific vehicle?’). Also, the impacts of contextualization as well as operationalization (discussed in chapter 4.2) on LCA results needs to be tested, analyzed and evaluated. One main aspect that would need special attention is the conduction of a sensitivity as well as an uncertainty analysis in cases of behavior operationalization based on social scientific data sets. To summarize this point, it is important to differentiate between the intended and actual use of a technology. This begins with the basic assumption made about a technology: while within the LCA studies it was generally assumed as a given, that SHTs should save energy and were purchased for this purpose, the social scientists argued for a more nuanced view on this matter. Of course, this also needs to be considered for other cases, like industry, mobility or ICTs.

With regard to methodological limitations the scope of the study was limited to the opinions and experiences of experts. This approach provides profound and well-founded insights, but results correlate strongly with the selection of the experts. All of the experts were identified on the basis of published and peer-reviewed works in order to ensure their expertise. Nevertheless, this approach carries the risk of bias in terms of overlooking other experts from the field. Also, it represents only a small section of the scientific landscape.

Concerning the execution of the interviews, a language barrier has to be considered, as only one of the experts was a native English speaker and the interviews were conducted in English. Regarding the analysis of the interviews, the category system as well as the code book were in accordance with the data protection agreement discussed with selected experienced supervisors and research colleagues. Nevertheless, the single-coder approach harbors the risk of subjectiveness and that information in the process may be overlooked or interpreted differently than in multi-coder setups.

5. Conclusion

The conducted study provides ideas for new approaches and implications for future LCA studies, combining interdisciplinary perspectives, research experiences, and practice know-how. It provides the basis for developing a comprehensive framework for the integration of behavioral effects in LCAs in the future, but already now assigns different social scientific conceptualizations to the steps of an LCA study. Problems concerning knowledge transfer – identified with regard to RQ1 – can partially be attributed to internal factors such as pragmatism, as well as to a lack of expertise or resources. However, external reasons such as an insufficient access to financial and time resources also play a major role. With respect to the results revealed within RQ2, ideas for an enhanced and differentiated application of social scientific methods within LCA studies were collected. In the comparative and comprehensive juxtaposition, the methodological implications deduced from the results of RQ2 were assigned to the LCA steps from the ISO norms. The here presented study, therefore, addressed the far under-investigated process of behavior operationalization in LCAs. In contrast to previous studies the research practice instead of the final research output was focused, to explore and derive internal and external factors hindering an enhanced integration of insights from behavior studies and social sciences by means of knowledge transfer. These barriers of knowledge-transfer as well as data processing between the research disciplines were discussed and can now be addressed accordingly in the future (e.g., by a stronger interdisciplinary cooperation between energy research, social sciences and LCA practice but also by funding plans that include resources for these types of study). For that matter and with respect to the comprehensive analysis of the interviews it is important to understanding social and behavior science not only as a form of ‘auxiliary sciences’, but as an equal contributor of knowledge and inputs for LCA studies. This study contributes to this aim, by aligning proposed social scientific and LCA practice, providing ideas for the contextualization of LCA results, the operationalization of behavior as well as on mixed-method research approaches.

6. Abbreviations

- ABM - Agent based modeling
- EI - Environmental impact
- G&S - Goal and scope definition
- ICT - Information and communication technologies
- LCA - Life cycle assessment
- “LCA_X” - Reference to the LCA practitioners with a consecutive numbering for the different interviewed persons
- LCC - Life cycle Costing
- SHT - Smart home technology
- sLCA - Social life cycle assessment
- STS - Science and technology studies
- “SOC_X” - Reference to the social scientists with a consecutive numbering for the different interviewed persons

7. Theory

7.1. Life cycle assessments

LCAs are a well established tool to assess the impacts of products and services and therefore also different technologies. They can vary in their goals and scopes and also have different purposes like the identification of environmental ‘hot spots’ or support in decision making. As

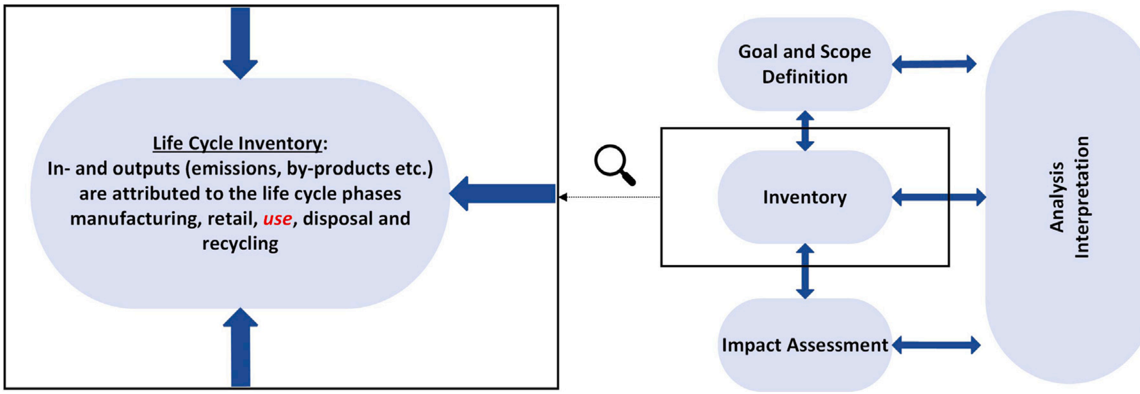

Fig. 9. Author, adapted graphic based on [12,13] and inspired by [53]. Shown in red is the attribution of the consideration of the use phase to the LCI.

much as these variations in scopes can lead to different methodological setups, the ISO norms 14044 and 14040 provide a general procedure for the conduction of LCAs [12,13]. In Fig. 3 this general procedure is depicted, highlighting the attribution of the use phase consideration and operationalization to the LCI.

As can be taken from Fig. 9, resource in- and outputs of any kind attributed to the use phase – that is most strongly correlated with behavior effects – are to be considered in the process modules defined within the LCI. Within this step of the data collection, for every phase of a product's/technology's life cycle the according resource in- and outputs are to be collected. The life cycle phases regarded are scope dependent, but can cover the resource extraction, processing, manufacturing, distribution, use and the end of life/recycling. For further information please refer to the ISO norms or other handbooks and guidelines (e.g. [54]).

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.

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Appendix

See Tables 5–8

Table 5
COREQ (COnsolidated criteria for REporting Qualitative research) Checklist, based on [39].

Topic	Question	Information
Interviewer	Which author conducted the interview?	The main author
Credentials	What were the researcher's credentials?	MA Cultures of the Technological and Scientific World
Occupation	What was their occupation at the time of the study?	Researcher & PhD student
Gender	Was the researcher male or female?	Female
Experience and training	What experience or training did the researcher have?	Experiences in the conduction of qualitative research in research projects funded by the German Federal Ministry and knowledge through study background.
Relationship established	Was a relationship established prior to study commencement?	Communication prior to the interviews took place via e-mail; the interviewer and interviewees did not know each other personally before the interviews.
Participant knowledge of the interviewer	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	In the e-mail contact established prior to the interviews, the experts got to know the name and occupation of the interviewer. Also, they were informed about the study context, which is a PhD study.
Interviewer characteristics	What characteristics were reported about the interviewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	The interviewees got to know that the research is part of a PhD study and received information on the general topic of the thesis. As the contact was also established through online research networks, the interviewees could find information on the interviewer's university degrees and study programs, in case they accessed the profiles.
Methodological orientation and theory	What methodological orientation was stated to underpin the study?	Content analysis, based on the deductive analysis approach suggested by Kuckartz and Rädiker [37].
Sampling	How were participants selected?	The participants were selected purposive. The process is described in the *context and participants* chapter 2.2
Method of approach	How were participants approached?	Participants were approached via e-mail or online research networks (e.g. Researchgate [40], LinkedIn [41]).

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Table 5 (*continued*).

Topic	Question	Information
Sample size	How many participants were in the study?	See method chapter 2.2
Non-participation	How many people refused to participate or dropped out?	A total of twelve experts were contacted, eight of whom were willing to conduct an interview. The others either did not respond to the requests or stated that they currently had no time or organizational capacity.
Setting of data collection	Where was the data collected?	Due to the distance, the interviews were conducted using a video conferencing tool. At the time of the interviews, the experts were either at work or working from home.
Presence of non-participants	Was anyone else present besides the participants and researchers?	Since the interviews were held online it cannot be guaranteed that no third person was in the same room or close by during the interviews. To the knowledge of the interviewer this was not the case, though, as there were no interruptions or interactions with other people during the interviews.
Description of sample	What are the important characteristics of the sample?	Comp. Table 1
Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?	A pilot guideline was tested with two fellow researchers before the interviews were conducted and revised based on their feedback. The guideline was not handed out prior to the interviews. Both interviews guidelines can be found in the appendix (tab. 7 and tab. 8)
Repeat interviews	Were repeat interviews carried out?	No.
Audio/visual recording	Did the research use audio or visual recording to collect the data?	As the interviews were conducted using a conferencing tool, the calls were recorded using the tools recoding and transcription function. Only the revised transcripts were used for the analysis, though (comp. also chapter 2.3)
Field notes	Were field notes made during and/or after the interview?	Handwritten notes were taken during the interviews in order to remember/organize consecutive queries and thoughts throughout the interview process.
Duration	What was the duration of the interviews?	The duration of the interview depended on the length and depth of detail of the answers given. The interviews lasted between 30 and 75 min.
Data saturation	Was data saturation discussed?	Data saturation was discussed with the supervisors and fellow researchers mentioned in the acknowledgments 8 after the third and fourth interview.
Transcripts returned	Were transcripts returned to participants for comment and/or correction?	No.
Number of data coders	How many data coders coded the data?	The main author coded the data. The category system and the coded section were discussed with the supervisors and fellow researchers mentioned in the acknowledgments 8, though.
Description of the coding tree	Did authors provide a description of the coding tree?	The coding tree is provided in Fig. 2. The category system in described in the appendix Table 6.
Derivation of themes	Were themes identified in advance or derived from the data?	As described in chapter 2.4, the themes and categories were identified based on the interview guideline, using the deductive approach based on Kuckartz and Rädiker [37].
Software	What software, if applicable, was used to manage the data?	The interviews were coded using MAXQDA [38].
Participant checking	Did participants provide feedback on the findings?	No, but the publication will be made available to them.

Table 6
List of codes used for the coding of the interviews.

List of codes	Memo	Count
1. Investigating behavior and practices	Within this main category all information concerning the methodologies as well as conclusions from social scientific studies on behavior of people in smart (home) environments were coded. This main category was exclusively used for the expert interviews with social scientists and anthropologists.	3
1.1. Correlation of behavior, energy and environment	By means of this category, text passages were coded that described the inter-dependencies between environmental impacts, the usage of energy and the human dimension. The category has its counterpart in the eponymous sub-subcategory within the *interdisciplinary exchange* category.	24
1.2. Encountered practices, behaviors and changes	In this subcategory, behaviors and practices that have been observed by the researchers are coded. The focus was primarily on behavioral changes that were induced or incentivized by smart technologies.	34
1.3. Methods	This subcategory was used to code text passages in which the social scientific methods used to investigate behavior were explained. Experiences, advantages and disadvantages were also subsumed here.	22
1.4. Users/Demographics	All statements and findings made on the topic of analyzed user groups were coded here.	26
2. Knowledge transfer	This main category was used to analyze ways and means of knowledge transfer between different disciplines. A distinction was made between the resources and ways that LCA practitioners have already used to obtain social scientific knowledge and ideas from social scientists on how this process could be facilitated or improved.	2
2.1. Interdisciplinary exchange (Opinions of practitioners)	This category contains the further sub-subcategories relating to the perspectives of LCA practitioners. The latter were used to code the statements on the transfer of knowledge from the social sciences to the practitioners' LCA practice.	7

(*continued on next page*)

Table 6 (*continued*).

List of codes	Memo	Count
2.1.1. Correlation of behavior, energy and environment	In order to understand how the LCA practitioners evaluate and assess the relationships between environmental impact, behavior and energy use, statements were coded in this category.	21
2.1.2. Objections & doubts	As objections were expressed against social scientific knowledge and/or the way in which it is achieved, the category was inductively added to the category system. Understanding reservations about other forms of science and knowledge can be seen as essential in order to reduce these in the future.	9
2.1.3. Perceived importance	In contrast to the reservations, positive aspects and the importance of social scientific research were also emphasized by the LCA practitioners. These are also essential to understand in order to identify which information in particular is relevant and valuable for LCA practice.	8
2.1.4. Ways to knowledge	There are different ways to obtain knowledge. In order to understand how knowledge should ideally be processed or which approaches have been used so far, statements on this have been summarized in this category.	15
2.2. Knowledge transfer from the social sciences into LCA	Complementary to category 2.1, this category summarizes the perspectives of social scientists with regard to the most important findings, improved communication and recommendations for the transfer of knowledge.	64
2.2.1. Ideas on quantification	With the aim of improving the quantification of behavior, approaches and ideas of social scientists were coded in this category.	18
2.2.2. Literature recommendations	As the social scientists were asked for concrete literature recommendations, these were coded within this category.	12
2.2.3. Most important practices/priorities	With regard to the results of the social scientific research, this category summarizes what the researchers consider to be the most important findings on the topic of 'behavioral changes' and 'practices in smart homes'.	3
2.2.4. Recommendations	In addition to the direct literature recommendations, further recommendations for an enhanced integration of social scientific knowledge were also coded.	23
2.3. STS perspectives	As STS focus explicitly on the interactions between society, humans and technologies, these theoretical approaches and insights were coded separately. Since some of the interviewed experts also incorporated these theories and perspectives in their research, they were coded in this category in order to distinguish them from the other findings and approaches.	21
3. Operationalization in LCA	This main category was used for the identification of the different approaches that were applied by the LCA practitioners with regards to the operationalization of user behavior in the use phase. Focus were – next to the identification of them approaches themselves – the reasoning behind the choices, as well as specific challenges connected to the use phase.	4
3.1. Approaches	In this sub-category the approaches described by the practitioners for operationalizing behavior in their LCAs were coded. The focus here was on questions about how they approached the assessment of the use phase and which methods or quantification approaches they used.	24
3.2. Challenges	Reported challenges with regard to behavior operationalization that could either be resolved by the practitioners or that were pending were coded in this category.	27
3.3. Reasoning	The argumentation for or against made decisions with regard to the approaches on behavior operationalization were coded in this category. The main concern here was to understand why the practitioners had decided for or against certain approaches.	17
4. Experiences/Background	In order to document and understand the professional backgrounds of the interviewees, this category was used to code what the experts reported about their scientific careers.	16
5. Other/Context	This category was set up inductively to code any additional information considered interesting or helpful and did not fit into any of the other categories.	16

Table 7
Guideline for the conduction of semi-structured interviews with LCA practitioners: The questions marked with an "•" are consecutive and were only posed when the information were not provided within the course of the given answer. The remarks in the *Check/Memo* column were used as reminders for the person conducting the interview.

Key question	Check/Memo
TOPIC A: Experiences with LCA	
What are technologies or products that you have conducted LCAs of? •Did you choose the product yourself?	Own interest? Contract/project?
How do you rate the necessity and importance of LCAs?	
What were the first steps you took when after you knew which product was going to be assessed?	ISO-norms? or literature research?
Considering that all different life cycle phases contribute to the overall environmental impact of a product – how would you rank the importance of the use phase?	
How did you approach the assessment of the use phase in your LCAs? •How did you decide on the parameters you used? •What are parameters you explicitly did not consider or investigate? •Which parameters would you like to use?	Why? (Access) problems?
Based on your experience: which role does the behavior of users play for the environmental footprint of a technology or product? •Did you consider in your LCA that people use technologies differently?	

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Table 7 (*continued*).

Key question	Check/Memo
What were your considerations when you approached the operationalization of user behavior? •Who are the users whose behavior or its impacts would you consider to be most relevant?	household dynamics/setups Representativeness (gender, age, sexuality, family status, income, occupation, care work)
[OPTIONAL: From what I saw you also conducted an LCA of smart home technologies: how did you approach the role that inhabitants play for the results of the LCA?]	scenarios, measurements, averages
How important do you consider the resource of energy and its utilization to be for the environmental assessment of technologies? (Water? Gas? Electricity?)	
TOPIC B: LCA of the future	
Imagine you are supposed to conduct an LCA of a household product – you can pick one of your liking – how would you proceed with regard to your former experiences? •Which documents/guidelines would you use? •How would you assess the use phase of [...]? •Are there specific guidelines or norms you would consider or use?	Example, if none mentioned: washing machine or stove
How would you define behavior?	
What is the relationship between technology, behavior and the environment for you?	
Do you think it would be fruitful to take a closer look at the use phase of technologies, especially of those used in households?	
Let us assume someone from outside your research field, for example a colleague from the social sciences, wants to provide you with information into the topic of user behavior for your next LCA. What would be the most valuable information for you and how should they be presented?	Behavior adaption? Energy intensity of usage?
Have you for yourself have ever used socio scientific research methods? •OPTIONAL: How were your experiences? •What were or would be the most valuable insights that you could gain?	Research context? Applied methods?
[TRANSITION: I would like to get back to the more general topic of LCA literature and guidelines] What were general challenges you encountered when you conducted LCAs?	
Did you find all the information you needed in the (LCA) literature? •Was there something that was missing for you?	Missing information?
When you think of literature on LCA methodology: what are the most important and relevant information for you provided there? •What did you like or dislike about specific guidelines?	
If there was a guideline on how to assess behavioral aspects – which information should be included, based on your experience? •What format should such a guideline have to be actually used?	
Would you consider using such a guideline in case you would need to conduct a product LCA again? •What would be your personal requirements in order to use such a guideline?	
Do you have any other comments or points that should be mentioned? Otherwise, I would like to make sure that I have all the relevant information: •Contact details for queries •LCA-experience •Professional background Close interview: possibles inquiries and thank you!	

Table 8

Guideline for the conduction of semi-structured interviews with social scientists: The questions marked with an "•" are consecutive and were only posed when the information were not provided within the course of the given answer. The remarks in the *Check/Memo* column were used as reminders for the person conducting the interview.

Key question	Check/Memo
TOPIC A: Social scientific research on SHTs	
What technologies have been objects of or in your research so far?	Own interest?
What are technologies or products you have investigated the usage of? • Did you choose the product yourself? • What were effects of technologies in smart homes you discovered/unraveled?	Contract/project?
What research methods have you used in your research so far? • Why did you choose these methods? • How were your experiences with the different methods?	Qualitative? Quantitative?
What were the first steps you took after you knew which product/technology/ ...was going to be assessed?	(Adapt question to the context)
In what way have you started to approach the investigation of user behavior/household practices/...?	(Adapt question to the context)
If they do, in which way play social and environmental reciprocal interactions with regard to user behavior/household practices for your research?	
What do you think are the main drivers for the development of smart home technologies and its usage? • To ask a bit provocative: which of these intentions are marketing? •...which ones can contribute to reducing the environmental impact of home making? •...which technological features actually can make life more comfortable for the inhabitants? •...what do you think are the main drivers for inhabitants to buy and use smart home technologies?	

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Table 8 (*continued*).

Key question	Check/Memo
Based on your experience: which role do environmental concerns play for the adjustment of user behavior to becoming accustomed to smart home technologies?	Economic or ecological reasons?
[OPTIONAL: Looking back at the research you conducted: what were general challenges you encountered when you started investigating the behavior of inhabitants of smart homes?]	
How did you come up with your test groups and households in your research? • Who are users whose behavior or its impact would you consider most relevant when it comes to environmental impacts? • Did you encounter the development of so-called unintended usages of technologies? (adaption of technologies at home?) • How did you come up with the selection of the inhabitant/user configuration you investigated?	Household dynamics? Representativeness: gender, sexuality, age, income, occupation, family status
What role does energy as a resource play for the intended change of behaviors? • Have you also been able to identify unexpected or unintended behavioral changes, and if so, which ones? • What are (household) practices that are easy and, respectively, hard to change?	
What do unintended and intended behavioral changes in your opinion mean for the ecological impacts of a technology?	
TOPIC B: LCA of the future	
How would you define behavior?	
Have you ever had a closer look on the environmental impacts of the technologies you are investigating?	
What is the relationship between technology, behavior and the environment for you?	
Imagine you are supposed to investigate how a household product is being used – you can pick one of your liking. How would you proceed?	
Based on your knowledge and impressions: how important would you rate behavioral aspects to be for the environmental impacts of a technology? • Taken, you are supposed to investigate and describe the success of a technologically incentivized behavior change – how would you proceed? • Do you think it is possible to somehow quantify behavior changes? If yes, how would you proceed?	Descriptive data or only quantification? Methods
Let us assume someone from outside your research field, for example a colleague who is an engineer, wants to start looking into the topic of user behavior and its assessment. Where would you say would be a good place to start? • Do you have recommendations on literature or guidelines for hands-on approaches? • What would based on your experience be suitable methodological approaches to identify practices or habits, that are prone to technologically posed incentives?	Recommendations?
One sometimes reads about user types or groups: from your experience, do they exist? • If so: how would you define them? • Were there common tropes or narratives you encountered from users concerning behavior adaptions, when you talked to them? • How do you rate the meaningfulness and value of clustering methods for identifying similarities between social groups?	
What are based on your experience the most important socio-demographic that influence people's usage of technological artefacts? • How would you weigh the influence of individual personality traits against socio-demographic or social factors concerning technology adaption? • Would an improved assessment of behavior effects be interesting for you and your research?	Individual impact vs. sociodemographic? Effects of interdisciplinarity on meaningfulness?
Do you have any other comments or points that should be mentioned? Otherwise, I would like to make sure that I have all the relevant information: • Contact details for queries • LCA-experience • Professional background Close interview: possibles inquiries and thank you!	

Data availability

The data that has been used is confidential.

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