Energy, Sustainability and Society

REVIEW

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Operationalising user behaviour: a study on the life cycle assessment of smart home technologies

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Abstract

Background Smart home technologies (SHT) make it easier than ever to track energy demands and are expected to contribute to the implementation of sustainability strategies. In particular, they are supposed to enable promising demand side management strategies by altering user behaviour towards sustainability while ensuring the balance of energy supply and demand.

For determining environmental impacts of products and technologies, the methodology of life cycle assessment (LCA) is an established tool. While large parts of LCAs are standardised, the consideration of user behaviour related effects has not been specified. By adopting an interdisciplinary perspective, this literature study contributes to the future development of a standardized methodology for the operationalisation of behaviour in LCAs.

Results Three main strategies for operationalising behaviour in LCA studies were identified: (1) behaviour theory-based approaches, (2) model-based behaviour predictions and (literature-based) deductions, and (3) averages and assumptions. The results of this literature study show that the selection of the strategy is crucial as the user behaviour and methods used for LCAs have a significant impact on the environmental and economic payback periods and calculated overall impact of SHTs. Findings from the social sciences on practices and household activities that can be influenced by SHTs, are not systematically applied.

Conclusions Our literature analysis makes it clear that LCA results depend on various factors. Selected operationalisation and methodological approaches, respectively, can play a key role. Depending on the method chosen the results can vary by several orders of magnitude and are not always comparable. Simplified approaches for integrating user behaviour into LCAs like assumptions and average values can be a first step in accounting for the relevance of behaviour. However, it is important to bear in mind that these approaches may not reflect actual user behaviour, as this can be subjected to a limited changeability of certain household practices and habits. On the basis of the results, the authors recommend greater interdisciplinary co-operation in the conduction of LCAs on SHTs, ranging from a common definition of the scope, to the implementation of socio-scientific research and survey methods, to the derivation of policies.

Keywords Environmental assessment, Smart energy, Demand side management, Use phase, Technology assessment

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Background

Smart homes and their users

Against the backdrop of the energy transition and the increasing proportion of intermittent electricity generation, e.g., from wind and solar energy, demand-sided control mechanisms have been widely discussed alongside storage options, regulations, efficiency and sufficiency to maintain stability in the electricity grid by balancing generation and demand [1–4]. Approaches including a high degree of user involvement are commonly referred to as demand side management (DSM), aiming at the introduction of a smart grid and load management with the purpose of keeping energy affordable and reaching environmental goals by decarbonizing electricity generation (ibid.).

Concerning the requirements for the introduction of future smart grids, smart metering devices can be considered the minimal technology needed in households (and industries) for the steps towards the 'smartification' of electrical power grids [5]. Smart meters are digital electricity meters—sometimes, but less commonly used in gas and water metering—which allow real-time feedback on energy consumption and automatization via an internet gateway [6, 7]. This gateway ensures the interconnectivity with other internet-enabled devices like smart phones and feedback systems like in-home-displays (ibid.). With the 'smartification' of energy production and consumption and the introduction of many new DSM-technologies over the last decade, 'smart' technologies not only have become part of many people's lives, changing work and private lifestyles, but have also become a part of legislative environmental and energy agendas as well as governmental policies [8–10]. Being a necessity for the introduction of smart grids makes smart meters a political matter as well: many countries are pushing their installation, often enforced like in the European Union (EU) [11–13]. Whereas some European countries like Sweden, Finland or Estonia already reported roll-out rates of up to 100% in 2020, this does not account for all countries in the EU [12]. Nevertheless, it is expected that the share of smart meters will increase significantly over the next years and up to a very high distribution rate [13].

If the 'smartification' of homes goes beyond the usage of a single metering and feedback device, these households can be referred to as being smart homes (comp. [14, 15]). The latter usually includes more diverse technologies which not only provide, e.g., heating, lighting or vehicle charging, but also use sensors and appliances to gather (real time) knowledge/data on the household to—independently of the inhabitants—control household settings like the temperature [16]. Such technologies from here on will be referred to as smart home technologies (SHT). As Darby [17] describes, definitions of smart homes differ mainly on if they are home- and user-focused or building- and system-focused. "*[...] what they share [though] is the significance of communications networks to link appliances or subsystems with each other and to enable remote access and control along with the provision of services*". While the shared idea of smart homes is the automatization of (energy related) tasks and can be regarded as aiming at taking away responsibility from users, smart meters in combination with feedback systems aim opposingly at giving more control to energy users and putting them in charge [18].

Taking a closer look at the implicit logic of user focussed DSM concepts, they are based on the notion, that the behaviour of (energy) users can be influenced through information, price control and other incentivisation like energy autarky or personal contributions to environmental sustainability [3, 19, 20]. According to Strengers [18, 21], they also centre around the idea that individuals can become their own smart energy managers, so they make rational, information-based decisions and do the (economically and environmentally) 'right thing' [18, 21]. Next to these user-enabling concepts a second smartification-based DSM strategy follows mainly the idea of the full automatization of households to become smart homes which relieves the residents of the responsibility for carrying out these tasks. Thus, these two main ideas differ primarily in the degree of involvement or responsibility of the residents (comp. also [17]). Both of the described strategies are nevertheless shaped by the idea that users—in this case household members—adapt their behaviours with respect to the requirements posed by the SHTs.

Environmental impacts of smart homes

The impacts of both strategies have though been discussed strongly controversial with regard to their actual influences on the (overall) energy usage [22], so their actual benefits, especially under environmental aspects, are not fully proven yet. According to a study on consumer footprints by Sala & Castellani "*79% of the climate change impacts, 84% of fossil resource depletion and 92% of the impact of ionizing radiation*" are, correlated with the use phase of different appliances, mainly associated with their energy usage [23]. These findings indicate the importance of the use phase of a technical appliance for its environmental impact. Nevertheless, they also raise the question of how interdisciplinary phenomena such as socio-ecological interactions are scientifically investigated, in this case specifically the dependencies of environmental impacts on user behaviour.

Concerning the assessment of environmental impacts and sustainability of products, the methodology of life cycle assessment (LCA) can be considered as one of the most common today, not least due to the fact the assessment process has been standardised for many years [24, 25]. It is often used as support in decision making for the development of more environmentally benign and overall more sustainable products. LCAs consist of four different steps that are highly dependent on each other. Namely, these are the goal and scope definition (GSD), the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation [24, 25]. They make up the framework for the calculation of environmental impacts caused by products, technologies, or services.

Although the LCA methodology provides a high degree of standardisation for large parts of the assessment, it also leaves freedom for methodological adjustments based on the scientific questions to be regarded (Ibid.). As noted by Polizzi di Sorrentino et al. [26] as well as Daae & Boks [27], for example, the consideration of user behaviour poses a major challenge. This, the authors argue, is particularly critical, since in many LCA studies the use phase accounts for shares as big as 50–80% of the total environmental impacts of products [28]. This is also in line with the above introduced results from Sala & Castellani [23]. Against the background of the simultaneity of the procedural requirements and the methodological freedoms, the question of how interdisciplinary dependencies are dealt with again arises. In addition, this apparent dichotomy makes LCAs a particularly interesting case study in terms of knowledge transfer between scientific disciplines.

Practitioners often have to rely on their own decision making when conducting an LCA. These decisions may include reasonable simplifications and assumptions, but can consequently lead to an inconclusive set of results [26, 27, 29]. Even though these simplifications and cut-off criteria have to be justified and communicated [24] they aggravate the across study comparison and derivation of recommendations for policy makers and users alike. Considering that a huge share of the environmental impacts of technical and digital devices is caused by the energy necessary for their operation, whereas the latter is dependent on their usage, it becomes evident, that an understanding of user behaviours is crucial when performing LCAs for these devices [26]. An additional challenge here is that the term behaviour is used in a variety of contexts and ways: against this background, Uher [30] describes a lack of a common scientific definition, making researchers rely "*on their intuitive understanding*" of this everyday life term. She points out the dependency of investigation and examination methods on the disciplinary field, the research is conducted in, ranging from questionnaire and self-report approaches in psychology and social sciences, to observations in biological fields (ibid.) and other life and natural sciences. Nevertheless, to assess the impact of behaviours, e.g., in form of use patterns, habits etc. within environmental assessments/LCAs, a well-grounded understanding of these human performances is necessary, whereby studies from the social and behaviour sciences as well as from the field of psychology provide insights on how behaviour changes can be scientifically approached (compare also [31]).

Research questions and study scope

The questions addressed in this review are derived from the interdisciplinary nature of the investigation of socio-ecological interactions described in detail above. The review's focus lies on the questions on how behaviour is operationalised in LCA studies of SHTs and with what consequences. LCAs of SHTs were selected as the object of investigation due to two main reasons. First, with their area of application in the domestic environment, SHTs offer options for highly individualised usage. Second, as described above, they are used to incentivise a change in energy use, which makes the behaviour operationalisation process especially suitable for the analysis. Explicitly, the following two research questions are addressed:

(1) How is behaviour operationalised (e.g., in the form of scenarios) in LCA studies of SHTs in terms of applied behaviour theories and other approaches?
(2) How are insights from behaviour and socio scientific studies on the influences of SHTs on users (household members) concerning their routines, practices and habits with respect to sociodemographic factors transferred and negotiated into LCA studies?

The following sections approach these questions as follows: first, which theories on behaviour or other ways to represent user behaviour were used in LCA studies, to understand how behaviour is perceived and negotiated by the LCA practitioners. With respect to this literature study's research question (1), it was of interest how user behaviour was operationalised in LCA studies so far. It was also addressed which role the users' behaviour plays for the use phase as well as which conclusions were drawn from these behaviour considerations in the conclusive steps of the LCA. Second, findings from socio scientific studies on the effects of SHTs of household members' routines, practices and habits are contrasted against the operationalisation of user behaviour in LCAs. Finally, recommendations were derived for future LCA studies based on the findings.

Method: literature search and selection

In this chapter, the methodological procedure for this study is outlined. An overview is given of the basic approach and how the procedure is derived from the research questions. This is followed by a more detailed description of how the literature was selected and analysed.

General approach

The aim of the study was to first generate an overview of the state of the art of behaviour operationalisation, using LCA studies of SHTs as case studies. It was investigated which scenarios concerning the energy usage behaviour were set up, which data types like consumption rates were gathered and which reverse conclusions were drawn from the LCA results concerning user behaviour. With respect to research question (2) on how are insights from behaviour and socio scientific studies on the influences of SHTs on users are transferred and negotiated into LCA studies, it was also necessary to identify—based on studies from the social and behaviour sciences—which routines, habits etc. were identified to be impacted by SHTs. Second, these findings were contrasted against those ones discussed and regarded in LCA studies. This comparison enables an enhanced estimation of the household activities for which social science data is available and how great the potential for change of these activities is assumed to be. It also generates insights into transdisciplinary information processing.

Literature search and selection

The procedure to address the research questions presented above is shown in Figure 1. A systematic

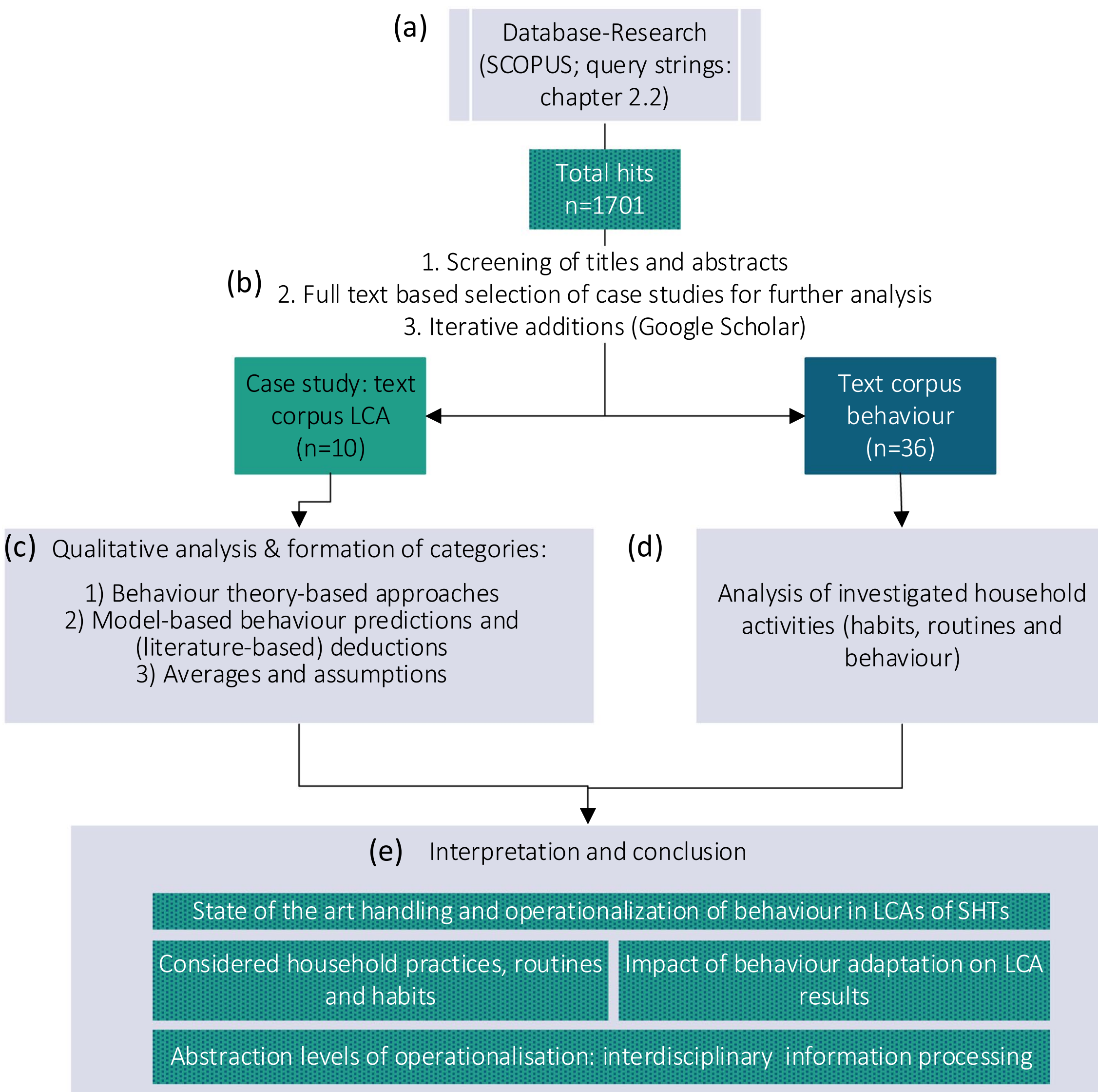

Fig. 1 Procedure of the systematic approach for the literature study carried out (own illustration)

bibliometric approach was set up with the goal to identify relevant studies which focus on the two areas LCA studies and behaviour of inhabitants in smart homes. In the interest of contextualizing the implementation of behavioural aspects, not only LCA studies were analysed, but studies from other research disciplines (mainly social science and psychology) which investigated the effects of a household's 'smartification' and the effect on its inhabitant's behaviour (referred to as 'studies on behaviour' in Figure 1 and from now on). Consequently, different search strings for the identification of LCA studies and behaviours studies were used in an iterative stepwise approach.

The database Scopus was used, covering the publication timespan from 1990 to 2022. The hits were limited to peer-reviewed articles, excluding book contributions and conference proceedings and were compiled in total for each query (step (a) in Fig. 1). Table 1 shows the search strings and the according number of hits:

The hits were based on their titles and abstracts prescreened and sifted through to exclude first spurious hits, false positives or those not relevant. The remaining articles were then further screened, to identify case studies on the implementation of SHTs in the different research fields. Following the goal of a contrasting comparison, the publications were catalogued according to their field of research (either LCA or behaviour studies). This step lead to two text corpuses, referred to as the result of step (b) in Fig. 1. In case of the LCA studies, those were kept that performed the assessment on SHTs excluding articles which only dealt with individual appliances (e.g., kitchen hoods or appliances for textile care). Concerning behaviour studies, articles were only kept where an actual application of SHTs took place, meaning that, e.g., lab-studies on display designs (for feedback apps or devices) as well as theoretical papers on, e.g., smart home algorithms were excluded. Due to the small number of peer-reviewed LCA studies on SHTs, another iteration of search query was performed, considering conference papers. Google Scholar was used to access iteratively identified or referenced literature, if they were not included in the text corpus after the initial database research (b).

Table 1 Search strings and number of hits for each query (in Scopus data base)

Search string	Hits
lca AND user AND energy	257
lca AND user AND energy AND smart	8
lca AND energy AND behav*	290
lca AND energy AND family	142
lca AND energy AND prosumer	4
lca AND smart AND home	12
environ* AND assessment AND smart AND home	203
Energy AND prosumer AND smart AND environment	37
Smart AND metering AND behav* AND energy	223
Smart AND home AND family AND energy	78
Smart AND home AND behav* AND energy	447
[Smart AND home AND behav*]	[1508; excluded in screening]

Analysis of the total number of articles

The screening was followed by an in-depth analysis, to answer the research questions (cf. chapter Research questions and study scope) for both LCA and behaviour studies. Thereby, MAXQDA 2020 [32] and Excel were used to set up an analysis grid and to compile data on the following attributes of the conducted case studies, their samples and results: demographics of study participants (age, income, gender/sex, education etc.), geographic setting, survey/measurement method, technologies assessed, sample size, household parameters (e.g., size, number of inhabitants, dwelling type), interconnection between behaviour and environmental impacts as well as addressed behaviours related to technology usage. These were chosen to generate an overview on the study settings and scopes, as well as on the generated insights on user behaviour.

With regard to the analysed LCA case studies the functional unit (FU), system boundaries, life cycle phases considered, LCIA method and addressed interconnections between behaviour and LCA results were noted. Adapting Kuckartz's [33] approach for qualitative text analysis, coding and category formation, the identified approaches for behaviour operationalisation were analysed and three main categories based on the analysis were formed (step c):

- Category 1: behaviour theory-based approaches
- Category 2: models and (literature-based) deductions
- Category 3: averages and assumptions

To generate the categories, the deductive-inductive approach for category formation by Kuckartz was used [33]. This approach starts with the application of pre-set—'deductive'—categories, but allows the adjustment, addition and omittance of categories based on the coding results. To our knowledge there are few preliminary studies concerning the implementation of behavioural aspects into LCA (comp. [26, 29]). Therefore, the overview of approaches on how to address behaviours in LCA studies provided by Polizzi di Sorrentino et al. [26] was used as starting point for the analysis and template for the deductively applied categories. The analysis of the LCA studies showed though that there were different approaches on behaviour operationalisation, which led to the formation of the three own above named categories. The theoretical backgrounds (applied behaviour theories, modelling approaches etc.) are explained in more detail in the chapter Conceptualisation and operationalisation of behaviour in LCA studies.

Results

The results are presented in the following subsections. First, the general findings on demographics, study settings etc. are summarised, to give an overview on the studies that were analysed within this research. Addressing research question (1), the results regarding the LCA case studies are presented in the following subchapter. The three main categories formed on the basis of the LCA case studies are introduced at the beginning of the subsections. The corresponding results are presented subsequently, addressing the connections between the approaches used for operationalising behaviour and their influence on the different LCA steps.

The result section closes with a contrasting juxtaposition regarding addressed habits, routines and household activities in the behaviour studies and the LCA studies, to answer research question (2). Information on study settings which provide insights on the representation of SHT users and can potentially correlate with knowledge and data transfer are also presented here. The aim here is to provide deeper insights on the findings and conclusions that can be drawn from the respective behaviour studies and the knowledge transfer between the scientific disciplines.

Before the results relating to questions (1) and (2) are presented, the LCA text corpus is briefly introduced below. A total of 10 LCA studies were analysed (Table 2) as well as 36 case studies on the behaviour of inhabitants of homes equipped with SHTs (see Table 1 of the supplementing materials). An overview of study scopes and coverages of the LCA studies is given in Table 2. As there are many different LCIA methods to hand, which can influence the study results considerably, which ones were used and which indicators were chosen for the published results was also analysed. As shown in Table 2, a manifold of different LCIA methods is being used, with an emphasis on different versions of ReCiPe. Regarding the indicators considered in the assessments the global warming potential (GWP) is mentioned in every study and it was found to be common, that only selected indicators were discussed in the papers. Except for the three studies from Walzberg et al. [34–36] on the impact of SHTs on households energy consumption, in all of the other studies the production/manufacturing, use phase and disposal/end-of-life were assessed. The considered product life span of SHTs differs with 1–30 years strongly between the studies, which is also reflected in the definition of the functional units (cf. Table 3).

Conceptualisation and operationalisation of behaviour in LCA studies

After the introduction of the text corpus, in this chapter the results concerning behaviour operationalisation are presented. In Table 3, information on behaviour related aspects identified in the LCA studies as well as further processing of these data are gathered. These include information on the operationalisation approaches, also on the household activities and practices that were addressed in the studies. It stands out, that there is a strong focus on heating, ventilation and air conditioning (HVAC) of homes, which are considered to be influenceable due to automation or feedback mechanisms. Within the other studies the overall energy consumption of households was the objective, mainly using average consumption data as inputs.

Furthermore, Table 3 provides information on the ways behaviour is being considered as influential on the LCA results. More explicitly, this means, whether behaviour is considered to have an effect, e.g., on the overall environmental impact of the technological devices, only within certain life cycle phases of the device or on a different note, if behaviour is being considered as influential on the environmental or economic payback times ('break-even points'). They all, most implicitly, reflect the often found promise that SHTs reduce the energy consumption of households.

The impact of the individual approaches on behaviour operationalisation are presented according to their categorisation in the following subsections of this chapter. A focus will also be put on findings that regard how behaviour aspects are implemented in the different steps of the LCA and how the chosen approaches influence the results of the assessment. As an adaption of Kuckartz's [33] approach of qualitative content analysis was applied, three main categories concerning the operationalisation of behaviour could be identified.

As previously stated, the behaviour theories suggested by Polizzi di Sorrentino et al. [26] were used as the starting point for the analysis of behaviour operationalisation approaches. The behaviour theories they suggested for addressing behaviour in LCAs are the following (sources adopted from ibid.): theory of planned behaviour [49], Triandis' model [50, 51], comprehensive action determination model [52], behavioural economics (including "*irrationalities*" or "*biases*") [53, 54] as well as the analyses of human interaction in social situations by [55]. The analysis showed, however, that none of these were used.

Table 2 Overview of identified studies and selected information on their LCA approaches.

Study	Considered Life Cycle Phases	Considered service life of technology	LCIA Method	Functional unit	Regarded Indicators
Louis et al. 2015 [38]	Manufacturing, use, end of life	5 years	Not explicitly mentioned, but congruent with ReCiPe 2008	Not explicitly defined, but according to own analysis: total impact of different HEMS over use of 5 years	Congruent with ReCiPe Midpoint (H)
Louis & Pongrácz 2017 [39]	Manufacturing, use, end of life	1 year	ReCiPe 2008	Not explicitly defined, but according to own analysis: EI of HEMS per inhabitant of a household per year	ReCiPe Midpoint (H)
Pohl et al. 2022 [40]	Production, use phase	10 years	ReCiPe 2016 v1.1 (H)	providing the service of energy management in a residence for one inhabitant over the period of 1 year	MD, GWP
Pohl et al. 2021 [41]	Production, use phase	5 years	ReCiPe 2016 v1.1 (H); USEtox 2.1; CML2001—Jan. 2016, elements	"110 m2 apartment space in Germany managed (monitored and controlled) for 5 years"	GWP, PED, ADP, Ecotoxicity
Scheepens and Vogtländer 2018 [42]	Production, use phase	30 years	ReCiPe H/A Europe (mPt)	Not explicitly defined, but according to own analysis: heating of 'living area' per m^2 to a comfort level over a lifetime of 30 years	Eco-costs/Value Ratio[a]; ReCiPe indicators (H/A Europe), carbon footprint
van Dam et al. 2013 [44]	Production, use phase, disposal	5 years	Not explicitly mentioned	Not explicitly defined, but according to own analysis: different HEMS (energy monitor, multifunctional HEMS and energy management device) over their lifespan of assumed 5 years	Eco-costs, CED, economic payback time
Walzberg et al. 2017 [36]	Use phase	1 year	Impact 2002+	Functional unit(s) vector representing [energy] consumption at a certain time *t* [kWh]	Human health, electricity consumption, ecosystem quality, costs, climate change, resource impact
Walzberg et al. 2019 [35]	Use phase	1 year	Impact 2002+	Functional unit(s) vector representing [energy] consumption at a certain time *t* [kWh]	Impact 2002+ indicators
Walzberg et al. 2020 [34]	Use phase	1 year	Impact 2002+	Electricity consumed [kWh] at a point of time *t* in 2011 by 100 standard smart homes	Impact 2002+ indicators
Weigel et al. 2021 [45]	Production, use phase, disposal	20 years	CML 2001	"German metering system"	GWP100, energy balance, resource depletion, HTP100

'H' refers to "Hierarchist: consensus model, as often encountered in scientific models, this is often considered to be the default model" [37]

Further used abbreviations are: *HEMS* home energy management system, *MD* metal depletion, *GWP* global warming potential, *PED* primary energy demand, *ADP* abiotic depletion potential, *CED* cumulative energy demand *HTP* 100—human toxicity potential (regarded over a time span of 100 years)

[a] According to [43], the "EVR [Eco-costs/Value Ratio] is […] an indicator to describe the eco-efficiency of a product and/or service. The EVR is a dimensionless number which indicates to what extent a (design of a) product contributes to the de-linking of economy and ecology"

Table 3 Overview of different behaviour related LCA properties and main findings of the studies

Study	Technology (as named in article)	Consideration of behaviour	Regarded aspects of behaviour at home	Identified impact of behaviour on LCA (results)	Main findings: impact on indicator-level
Louis et al. 2015 [38]	Home Energy Management System (HEMS)	Average energy consumption of a Finnish 4-person-household is considered as well as a 12% reduction of energy consumption	General usage of energy (no specific practices)	Influence on share of different life cycle phases	99.4% of the emissions occur during the assembly and the use phase, where the use phase represents 84%; environmental payback cannot be reached within 5 years of usage
Louis & Pongrácz 2017 [39]	HEMS: Smart metering with feedback; smart home	Average energy consumption; expected energy savings are considered and compared to automated smart home energy management configurations	General usage of energy (no specific practices)	Influence on share of different life cycle phases	The use of smart meters causes 14.8 kg CO_2-eq/y; fully deployed HEMS cause 78 to 114 kg CO_2-eq/y (dependent on no. of inhabitants)
Pohl et al. 2022 [40]	Smart home	Rebound effects [RE], average reduction of heating demand due to smart home system	HVAC; purchasing of smart home technologies	Influence on environmental performance of smart home system with regard to different indicators (GWP, MDP) and the primary energy demand (PED)	GWP: impacts of -991 kg CO_2-eq to 804 kg CO_2-eq per capita per year; owning a SHS (with smart heating) leads to overall reductions (M(SD) of -35 (240) kg CO_2-eq per capita) in 55% of cases
Pohl et al. 2021 [41]	Smart home	Framework of environmental effects of ICT [46, 47] and [48]: purchasing behaviour, required savings	HVAC; purchasing of smart home technologies	Composition of smart home setup; estimation of required minimum saving needed for environmental payback caused by production and operation	- GWP: net savings from 381 kg CO_2-Eq. (6% saving scenario) to 3423 kg CO_2-Eq. (20% saving) scenario in 5 years. Payback time between 6 months—2.4 years - PED, net savings 3533 MJ for the 6% scenario and 51,228 MJ for the 20% scenario (5 years); payback time 6 months to 3.1 years
Scheepens and Vogtländer 2018 [42]	Smart temperature control	RE, comfort-models	HVAC	Influence on the point of economic and environmental investment payback	Compared to the baseline the heating demand could be reduced by 14.5–40% (dep. on radiators / floor heating), whereby 40% are considered unrealistic because of comfort losses; the pay-back time for the so considered most-likely configuration is calculated to be 20 years

Table 3 (continued)

Study	Technology (as named in article)	Consideration of behaviour	Regarded aspects of behaviour at home	Identified impact of behaviour on LCA (results)	Main findings: impact on indicator-level
van Dam et al. 2013 [44]	Home energy management system	RE, fall back and energy saving potentials	General usage of energy (no specific practices)	Influence on the point of economic and environmental investment payback	- Within 2 years all HEMS reach the environmental break-even point, independently of the saving scenarios - The simplest HEMS reaches the break-even point earliest. If no energy is saved due to behaviour changes, the break-even point might not be reached
Walzberg et al. 2017 [36]	Smart home	Kaiser's concept of difficulty (based on Campbell's Paradigm); RE; average consumptions	HVAC	Effect of behaviour and RE on the environmental performance of a smart home system with regard to different indicators	Mean reductions of electricity consumption, cost, human health, ecosystem quality, climate change and resource impact – due to energy feedback – of about 2.0 (±0.5) %
Walzberg et al. 2019 [35]	Smart home	Campbell's Paradigm, average consumption	HVA; different device usages (e.g., freezer, lighting, etc.) considered	Effect of behaviour and smart home settings on the environmental performance of a smart home system with regard to different indicators	- Overall electricity consumption and costs reduced by 2.1 ± 0.4% - Ozone layer depletion (midpoint): impacts decreased by 2.1 ± 0.4% (4.04E- 04 ± 6E-05 kg CFC-11eq avoided) - Land occupation midpoint impact 1.9 ± 0.3% decrease in the category (4.77E + 01 ± 7E + 00 m^2 organic arable land avoided)
Walzberg et al. 2020 [34]	Smart home	RE (consideration of min. and max. GHG emitting commodities), Campbell's Paradigm	HVAC; different device usages (e.g., freezer, lighting, etc.) considered	Effect of RE on economic and environmental saving potentials with regard to GHG emissions and financial savings	- Electricity consumption: decrease of 1.7 ± 0.3% - GHG emissions: decrease of 3.3 E + 04 ± 2 E + 03 kg CO_2-eq (i.e., a 10.2% reduction in climate change impact) - Economic effect: saving of averagely 37.8 CAD; if respend: 4.7 ± 0.4% indirect RE in GHG emissions occurs

Table 3 (continued)

Study	**Technology (as named in article)**	**Consideration of behaviour**	**Regarded aspects of behaviour at home**	**Identified impact of behaviour on LCA (results)**	**Main findings: impact on indicator-level**
Weigel et al. 2021 [45]	Smart meter	Average consumption	General usage of energy (no specific practices)	Effect of smart metering induced energy savings with regard to GWP, energy balance, HTP and resource depletion	Total smart meter lifetime GWP is calculated to be 558 kg CO_2-eq, the one of conventional meters 211 kg CO_2eq.; when considering behaviour and energy system related saving effects though, a reduction of 23.9 Mio t CO_2-eq (over 20 years; GWP 100) is calculated

Therefore, own categories were formed, clustering the applied approaches according to their commonalities and inherent logics (see Table 4). These approaches and theories that have been summarised in the three categories are explained at the beginning of each of the following sub-chapters.

Following the presentation of the category, the respective analysis of the studies is presented. The first category to be introduced is the one on the usage of behaviour theories (1. Category: (behaviour) theories), meaning, that in these studies a theoretical approach was chosen to represent or substantiate behavioural effects. The second category is the usage of (not necessarily behaviour) models that are used for the latter (2. Category: models and (literature-based) deductions), where, e.g., behaviour predictions are made with help of comfort models, but also based on specific insights from the literature. In the third and final category (3. Category: averages and assumptions) the effects of assumptions as well as averages are presented. In addition, underlying and implicit assumptions that were identified in the LCA studies concerning the behaviour of users/inhabitants are described in this chapter.

1 Category: (behaviour) theories

Category description: In this chapter the first category of identified operationalisation approaches is introduced. It subsumes (behaviour) theories that were used in the LCA studies to operationalise behaviour. The introduction is then followed by the description of their according impacts on the LCA studies.

The first theory identified was an adaption of the so-called Campbell's Paradigm for Attitude Research. The paradigm was first introduced by Campbell [56] and draws a connection between attitude and behaviour research. It has been used mainly in behaviour explanation and prediction [57] and recently been adopted and further developed, e.g., by Kaiser et al. [58], who drew their evidences "*mainly from work in environmental psychology on ecological or pro-environmental behavior [sic!]*".

A different approach that was identified as theoretical framework for addressing behaviour in LCA studies is the one of environmental effects of information and communications technology (ICT), which is based on the work of Berkhout and Hertin [46], Hilty and Aebischer [47] as well as Pohl et al. [48]. Berkhout and Hertin [46] introduced the differentiation of three main impacts, ICT technologies can have, which are:

– "*First order impacts: direct environmental effects of the production and use of ICTs*

- *Second order impacts: indirect environmental impacts related to the effect of ICTs on the structure of economy, production processes, products and distribution systems*
- *Third order impacts: indirect effects on the environment, mainly though the stimulation of more consumption and higher economic growth by ICTs ('rebound effect')."*

Pohl et al. [29] further developed this framework and differentiated between product parameters and use parameters concerning the implementation of user driven parameters in LCAs.

Even though the theory of rebound effects (RE) (also called Jevon's paradox) originates from economy research, in the analysed studies the RE is often treated in a similar way to behaviour theories and is, therefore, discussed in this category. The RE describes the phenomenon that positive effects (for the environment) achieved through higher efficiencies can be offset by higher usage rates of the device itself or by expanses on / usages of other devices [59]. Sonnberger and Gross [59] provide a brief overview on the state of research on RE and refer to the definition by Azevdo [60], who describes the RE as "*the gap between engineering assessments of potential energy (or emissions) savings [...] and actual energy (or emissions) savings [...] that are measured after the energy-efficient technology or measure is adopted*". In addition, they distinguish between the direct rebound effect, the indirect rebound effect and the economy-wide rebound effect [59]. In summary, all REs lead to a relativization or reduction of positive environmental effects that are achieved through (energy) efficiency improvements.

Impacts on LCA studies: Starting with the Campbells Paradigm, in the analysed LCA studies a modified version of this theory was used by Walzberg et al. [36] as input for their agent based modelling (ABM) approach. To get the input for their model, they used the factors from the Campbells Paradigm to predict user behaviour, if they would live in a smart home. Concerning the choice they made for using this particular theory, they argued that another very commonly used theory for behaviour analysis and prediction, the so called *theory of planned behaviour* was not able to represent gaps between attitudes and behaviour changes in an adequate way necessary for their ABM approach [36]. In brief, the Campbells Paradigm allows to circumstantiate a relationship between peoples' attitudes and their behaviour: "*That a person acts in a particular way, therefore, is anticipated to be a function of two components: (a) the person's disposition, for example, the level of his or her environmental attitude, and (b) the specific difficulty of the particular behavior, which is the composite of the costs involved when enacting the behavior*" [58]). An adaption of the Campbells Paradigm was used to calculate the "*probability of engagement in pro-environmental behaviors* [sic!] *following energy feedback*" [36]. Within three studies by Walzberg et al. [34–36] only the use phase of SHTs was assessed, with the shared conclusion that the energy consumption within households would decrease by about 1.7–2.0% (ibid.; comp. also Table 3). Within the ABM approach the theory was, therefore, used to calculate hypothetic energy savings and energy related reduced environmental impacts on the LCA level for the use phase of the SHTs.

The second theoretical approach to be discussed in this category is an adaptation of the framework of environmental effects of ICT, used by Pohl et al. [41], first introduced in Table 2. This is an adaptation of the framework of environmental effects of ICT, from which only selected aspects were included in the methodological implementation of their actual LCA. Other than the Campbells Paradigm, the framework of environmental effects of ICT can be considered more focused on (household) practices instead of general behaviours and relates the practices with environmental impacts.

The aim of the study conducted by Pohl et al. [41] was the identification of the environmental break-even point of smart heating systems, so, to identify the energy savings that are needed to equalize the environmental impacts that are caused by the production and operation of the systems with a limitation to the production and use phase. For their study, they selected different user-driven parameters. They associated the latter with the environmental impacts noted in the brackets, respectively [41]: use parameters (rebound effects), product parameters (first order effects / induction effects), socio-demographic information (-), literature based product parameters (optimisation effects) and technology parameters (first order effects). To gather information on the use and product parameters, they conducted an online survey, using the theory on inhabitants' behaviour as basis for an own enquiry. Interestingly, the information gathered on the configuration of the smart home was used for the definition of the product system, acknowledging the users beforehand purchasing behaviour. Furthermore, information on the operation and the socio demographic information of the users was gathered via the survey. With regard to the further operationalisation of the gathered data next to the definition of the product system, saving scenarios of 2%, 4%, 6%, 10%, and 20% of the annual heating energy demand (Germany) were regarded within the LCI phase of the LCA (ibid.). Concerning the LCIA, their results indicate that over the

Table 4 Identified approaches of behaviour operationalisation and according studies

Category	Approach of behaviour operationalisation	LCA studies
1. (Behaviour) theories	Campbell's Paradigm for Attitude Research; Rebound effects; environmental effects of information and communications technology	Pohl et al. [40]; Pohl et al. [41]; Scheepens and Vogtländer [42]; van Dam et al. [44]; Walzberg et al. [36]; Walzberg et al. [35]
2. Models and (literature-based) deductions	Fanger Model for thermal comfort; selected findings from literature	van Dam et al. [44]; Walzberg et al. [34]
3. Averages and assumptions	(Country-specific) averages on energy usage, assumptions	Louis et al. [38]; Louis & Pongrácz [39]; Weigel et al. [45]; Walzberg et al. [34]; Pohl et al. [41]; van Dam et al. [44]; Louis & Pongrácz [39]

course of the regarded 5-year time span the GWP and primary energy demand (PED) can be lowered compared to the baseline, if the heating demand is reduced by 6%, 10% or 20% due to smart heating. This does not account for the abiotic depletion potential (ADP) and ecotoxicity, however, as the caused environmental impacts of the production phase are greater than the savings caused by a lowered heating energy demand. These results show not only the dependency of the LCA results on the operationalisation of behaviour for the use phase, but as previously discussed, also of the LCI. Pohl et al. [40] elaborate on those two different parameter types: "*By choosing different devices and settings, the user consciously or unconsciously determines product parameters. Product parameters include choice of products (in number and size) and services and choice of additives. Accounting for user behaviour with regard to product parameters reveals how user decisions can have an effect not only on the use phase but also on the definition of the product system*".

Next to these approaches, the analysis of the LCA studies [34, 36, 40, 42, 44] showed a very striking ubiquity of the RE: money saved through smart devices is considered to be spent on new technical artefacts or environmentally harmful activities. REs were the by far most considered theory based expected behavioural effect: they were discussed in different forms and to different extents in the LCA studies and were approached in different manners. Walzberg et al. [36] for instance explain the consideration of the RE in LCA studies as a necessity due the specifics of ICTs: "*While LCA is a standardized methodology, several limitations exist when applying it to ICTs and their applications: rebound effect may appear (as ICTs usually improve systems' efficiencies) which requires complementary tools to LCA, and results are highly dependent on human behaviors* [sic!] *and therefore need to be explicitly considered in the LCA* [61]." Also, Scheepens & Vogtländer [42] point out the importance of the RE, focussing on the relativization of positive energy savings effects due to the spending of saved money on other means.

The example of REs shows that even (supposedly) similar behavioural effects are parameterised and operationalised differently in the LCA studies that were examined. With regard to the implementation of the REs in the LCA, they are already included in the scope of the studies in the GSD. Nevertheless, this consideration is approached in different ways. As saved money is thought of being spend on environmentally unfriendly or harming commodities, e.g., Walzberg et al. [34] and Scheepens & Vogtländer [42] developed LCI-scenarios that are supposed to represent spending on maximum and minimum damaging activities or products (e.g., spending money on travelling or house refurbishments [ibid.]). To investigate the expected effects, Walzberg et al. [34] used an ABM approach to simulate these different effects during the use phase, whereas Scheepens & Vogtländer [42] used the so called eco-costs/value ratio to investigate the sustainability of buying behaviour and its influence on the economic and environmental payback time.

2 Category: models and (literature-based) deductions

Category description: Differently to the theory-based operationalisation of behaviour, in some studies selected insights or specific scientific findings were used for the operationalisation of behaviour and its effects. Many identified studies from the socio scientific field investigated how people adopt their behaviours when new (disruptive) innovations like SHTs are introduced to their homes [48–50]. Whereas some new habits may emerge, there also can be so called fall-backs to old routines and practices that relativize behaviour induced energy savings and/or bring the energy consumption back to an old or new (higher) baseline. If these specific insights were chosen to operationalise behaviour in LCA studies, they were coded within this category. In addition, instead of using a direct approach on modelling 'behaviour', higher abstracted approaches were identified, like the Fanger Model for thermal comfort [51]. The latter can be used to model the thermal comfort for different rooms, accounting occupancy, time of the day, temperature etc. and was used to draw model-based conclusions on possible (heating) behaviours of the inhabitants.

Impacts on LCA studies: One example of this operationalisation approach was, e.g., found in van Dam et al. [44]. There the authors argued in reference to Abrahamse et al. [62] and Darby [63], that a new, lower baseline consumption might be established when a home energy management system (SHTs) is introduced in a household: "*reductions of 2%, 4%, 6%, 8% or 10% [energy] savings were hypothetically achieved, in comparison to the preintervention*" compared to the Dutch average consumption. These hypothetical savings would also fall into the category 3, but additionally they created one scenario in "*which for the first half year gas and electricity savings of 8% were achieved, and that in the consecutive year savings dropped to 4%, after which consumption increased to the original levels for half a year. In the remaining three [of the considered five] years, the gas consumption did not change [0% change], while the electricity use resumed to follow the national trend by increasing by 1.5% per year* [64]" [44]. The scenarios were set up to investigate the influence of energy savings on the environmental break-even point of different home energy management systems. The perception of behaviour in this case led to the 'translation' of these behaviours into different energy and gas consumption rates, leading to a dependency of the environmental payback times within the LCIA on the according energy saving scenarios. The considered behaviour fall back has an impact on the outcomes of the CED as well as on the economic savings: as the savings are considered to be great in the beginning, the CED break-even point for all different considered devices equals the one of the 8% and 10% constant saving scenarios. Concerning economic savings, the authors come to different results: whereas for all constant saving scenarios at least for the simpler devices economic savings can be realized, those economic advantages will not be achieved in the fall-back scenario, but consumers pay according prices [44]. However, the authors state that "*from an environmental perspective this [the lack of a return of investment] is not necessarily a negative outcome: it can prevent a RE thereby households invest the saved money in other energy intensive products or services*", referring back to the already discussed REs and putting them in perspective.

Concerning a further identified approach to account for inhabitants' behaviour if SHTs are introduced in a household, Scheepens & Vogtländer [42] used the Fanger Model for thermal comfort. The model's framework was used to regard possible behavioural effects related to thermal comforts in apartments. In their case study the model was applied on a two-story house that is equipped with different configurations of thermostats that regulate the temperature in the rooms depending on the day or night time and their occupancy. After modelling different possible temperature configurations, it was assumed that inhabitants would only tolerate little changes when it comes to their comfort and would overrule the smart technologies to regain their comfort: "*Even if the more intelligent thermostats are considered, which are designed to diminish the hassle of programming and adjusting the settings by 'sensing/learning' the user's behaviour, the physical heating system will require a 'heat-up time', resulting in thermal discomfort if the occupants deviate from their usual behaviour. This will eventually lead to users overriding the automatic programming, and decreasing the energy savings*" [42]. Based on perceived losses of comfort it is, therefore, assumed that users would not tolerate the highest achievable savings that would be possible due to automation.

Interestingly, the authors also make a connection to the rebound effect, similar to van Dam et al. [44], stating that longer financial payback times may decrease the probability of rebound effects, as financial savings might not be as noticeable on a large scale.

3 Category: averages and assumptions

Category description: In this third category other approaches were coded and included that did not fall into the two categories described above. The LCA methodology requires on the inventory level an input of quantifications that are needed as base for the calculation of environmental impact of the services or products, respectively. As there are often no primary data sets available, a common procedure is the use of averages as input. Averages are often used as comparably easily accessible input data, especially as baselines for scenario setups. Averages in this case concern, e.g., country specific energy mixes (share of renewables, nuclear power etc.) but also consumption averages. In addition, other implicit or explicit assumptions that were made by the LCA practitioners as well as their impacts on the operationalisation were coded in this category.

Impacts on LCA studies: As already stated, the importance of behaviour for the conduction of an LCA for smart home technologies was acknowledged in all of the analysed LCA studies. However, not all of these studies used specific theories or models to operationalise user behaviour, but also informed conjectures. The influence of implicit and explicit assumptions as well of the usage of averages in LCA studies, is presented and discussed in this category's subchapter.

Assumption can and sometimes have to be made in cases of insufficient data availability and ideally should be communicated as such. An example for the application of an assumption can be found in Weigel et al. [45]. In pursuance of determining the perceived energy savings made concerning the usage of smart meters, they refer to a study by the German Federal Ministry for Economic Affairs and Energy that "*[...] assume[s] an average energy saving of 1.8%*" [45]. The adoption of assumptions from the literature here was clearly communicated. Again, the use phase was considered to be impacted by the users' behaviour and the assumption was used to depict this supposition.

Concerning more implicit or underlying assumptions about users' behaviour a rather unchallenged application of average values was observed in the LCA studies. This accounts particularly for the usage of country or region energy consumption averages that were used as baseline scenarios (e.g., for Ontario/Canada [34], Germany [41], the Netherlands [44] or Finland [39]). Energy savings that were expected to be induced by the SHTs where then applied to the baseline consumption and environmental benefits were calculated accordingly within the LCIA.

The technical or structural parameters of households are sometimes discussed with regard to how the average values are obtained [34, 44], or energy consumption is related to the number of inhabitants [39]. However, the reference to behaviour is generally not discussed when using average values.

Framing the users: specific habits, routines and practices

In this subchapter research question (2) is addressed, contextualising findings from the LCA studies and the analysed studies from the behaviour and social sciences. As mentioned in the methodology chapter, background information on the studies was also gathered. As sociodemographic factors (like age, gender, education, income etc.) can provide useful insights on the general settings and representativeness of studies and potentially correlate with user behaviours, they are presented here. First of all, information on the geographic setting of the studies was gathered (Fig. 2), as the consumption of resources like water, energy etc. can be strongly shaped by cultural practices and expectations [65, 66].

The majority of both LCA and behaviour studies was conducted with Europe as the study location, followed by North America and Australia, suggesting a Western-centric focus and view in the studies, therefore, meaning simultaneously, that the analysed LCA studies were conducted using country specific data from Western World countries like Canada [34], the Netherlands [42, 44], Finland [39] or Germany [40]. Following this analysis, the composition of test groups concerning gender and age representations were also analysed, as presented below.

The composition of test groups is a crucial point for the fair representation and meaningfulness of studies in various fields [67]. Concerning the investigation of gender biases in science and technology research, the underrepresentation of other genders than the male one has long been criticised [68, 69]. Within this context, numerous studies have also shown that gender performance and gendered household practices can impact the adaption, usage and acceptance of SHTs [70–72]. Against this background, it was analysed whether gender was considered in the composition of the test groups and / or if gender-related behaviours were investigated. The average distribution of gender in the behaviour studies was calculated from the data of the individual distributions from the studies, if the latter was given. As can be taken from Fig. 3, along with the studies [40] and [41] there were only two LCA studies providing information on the gender of their test group participants (both studies referring to the same survey data set). Concerning the behaviour studies, at least 17 out of 36 provided this information. It can be taken from the figure, that on average there is still an underrepresentation of people identifying as female in the studies, not to speak of a missing representation of people of other genders than male and female. As mentioned above, technology acceptance as well as household practices and dynamics can—according to [70–72]—be impacted by peoples gender. Therefore, it should be aimed for equal gender representations in test groups.

This is also true for the representation of different age groups as age can play a role in the openness to as well as the ease of learning about and the handling of new technologies [73, 74]. This data was collected and is depicted in Fig. 4. As the results show, the majority of the studies did not indicate the age of the participants. Many of the behaviour studies cover diverse age groups, whereas only four of them are concerned with elderly people and three with young adults (or more specific students).

Following the analysis of geographic setting, gender and age, an attempt to analyse the other sociodemographic factors was also taken. Due to too large variations in data enquiry, collection and presentation concerning these factors in the analysed studies that did not allow a comprehensive data abstraction, no broader conclusions could be drawn in these cases.

After introducing the different settings of the study types this following subsection will address how the findings on SHT-induced behavioural changes from the social and behavioural sciences are discussed in more detail. It should be noted beforehand that the scientific

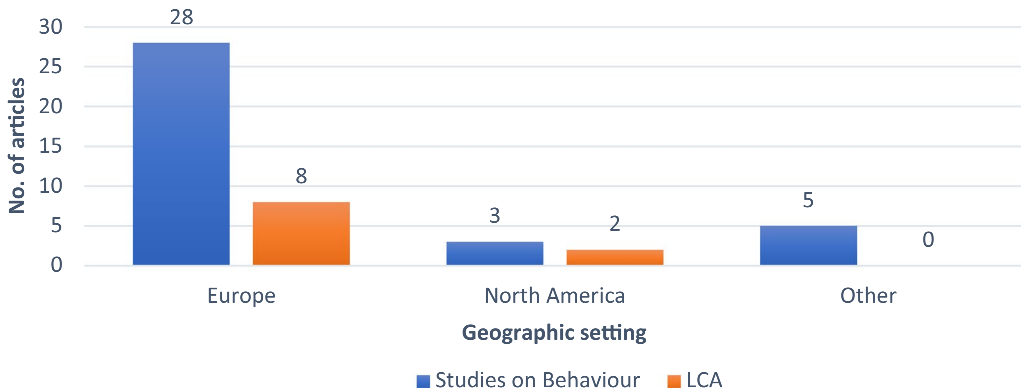

Fig. 2 Geographic setting of studies considered in life cycle assessment (LCA) and behaviour studies for smart home technologies. The category 'other' refers to Asia, South America and Australia, as well as studies without a specific geographic setting (own figure)

disciplines clearly have different research interests and use different methods the authors of this paper are aware of. Therefore, the focus of the analysis is not only the knowledge-transfer between disciplines, but also of the transformation of knowledge and information as well as the process of data abstraction. This will be discussed in the context of an epistemologically inspired concept of data transformations in Adriaanse [75] and Linser [76]. First of all, results from the analysis of the behaviour studies are presented and contrasted against the operationalisation of behaviour in LCA studies. To analyse which household activities were taken into account in the social and behavioural science studies, the household tasks discussed in these studies were first generally determined inductively.

Figure 5 shows that the largest share of studies discusses the HVAC behaviour of the inhabitants. Nevertheless, the data also shows a broader and more diversified picture of tasks and activities which can take place in a home having an impact on the energy consumption, regarding more explicitly the influences of SHTs on dimensions of home making other than thermal comfort. Referring to Shove et al. [77] and Macrorie et al. [78], also Naus & van der Horst [79] argue interventions like energy feedback should be seen "*as part of a configuration (or: system) of heterogeneous practices*". In their study on smart meter feedback systems in a community, they found that, especially practices like doing the laundry, were hard to change for many study participants, as they highly correlate with time management at home as well as expectancies, concerning for example cleanliness [79].

Discussion

The results presented in the previous chapter are reflected as follows with reference to the research questions posed at the beginning, starting with the discussion of the found handling of behaviour in LCA studies conclusions that can be drawn from these findings. As the chosen methodological approach of this study was mainly qualitative the conducted quantifications (e.g., Fig. 3–Fig. 5) should be seen as tendencies. Since the aim of this

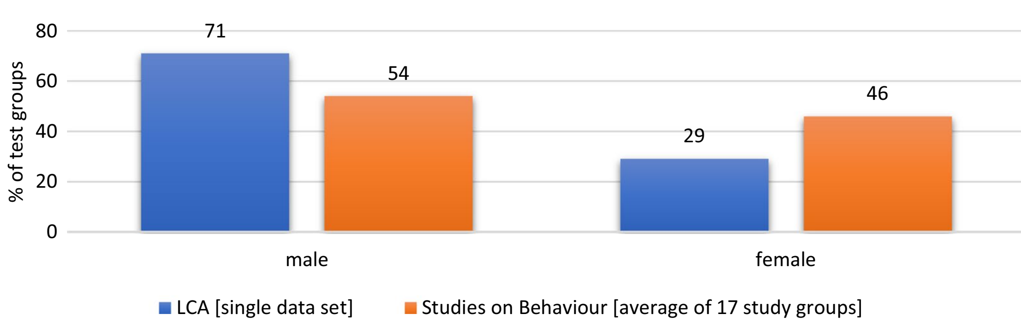

Fig. 3 Composition of the test groups related to the gender of the participants, if specified in the studies (own figure). The life cycle assessment study is a single data set used by Pohl et al. [41] and Pohl et al. [40], as the other studies provided no further information on the gender of their test households members. The data set of the latter two studies was the only one that included 0.3% participants of other genders than male and female

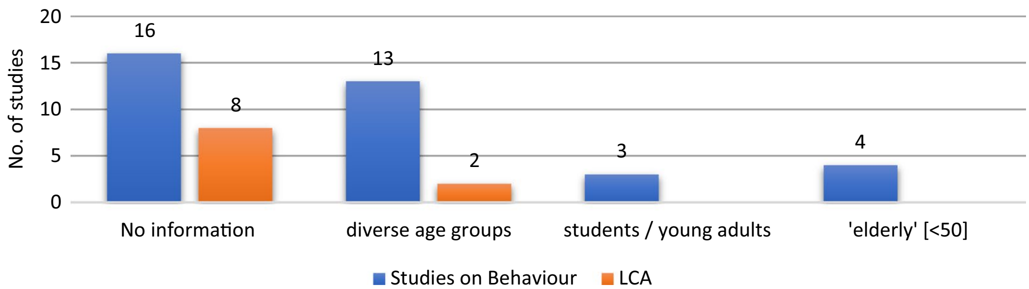

Fig. 4 Representation of specified age groups in LCA and behaviour studies (own figure)

study was the development of a deeper understanding of interdisciplinary dependencies and knowledge transfer between scientific disciplines, it does to its rather narrow scope not provide an overview of the respective fields as a whole. In this light it has to be noted that especially the LCA text corpus, consisting only of ten studies, was comparably small. However, it reflects, that the LCA side of the topic of SHTs is still under-investigated. Nonetheless, the main focus of this work was to identify, particularly on a qualitative level which approaches on user behaviour operationalisation in the SHT field have so far been applied. In this context insights on the influence of the operationalisation approach could be drawn, even though these should be put into a bigger context in the future, considering the usage of further (smart) technologies. This could be reached by the application of broader search strings for the literature search and the subsequent inclusion of LCAs of more diverse technologies used in home contexts.

Operationalisation of behaviour in LCA of SHTs

As seen in the results chapter, the analysis of the LCA studies revealed a very diverse picture with regard to the operationalisation of behavioural aspects. The different understandings of behaviour described by Uher [30], nevertheless, are strongly reflected in the analysed papers of the LCA case study text corpus. In particular, the 'intuitive understanding' and major disciplinary differences to study the topic of behaviour described were evident due to the fact that different approaches were chosen to address the behavioural aspects, with a strong focus on REs. Noteworthy about this finding is, first of all, that the concept of REs does not emerge from behaviour or social science, but economic theories. Second, with this focus an emphasis is being put on environmental effects that are not caused by the SHTs themselves or their usage, but by the (re-) investment of money previously saved.

The results presented in chapter 1. Category: (behaviour) theories show that the analysed studies are not directly comparable due to the different used FUs, GSDs, LCIs and also LCIA methods. In addition, the behaviour theories can for instance be used as

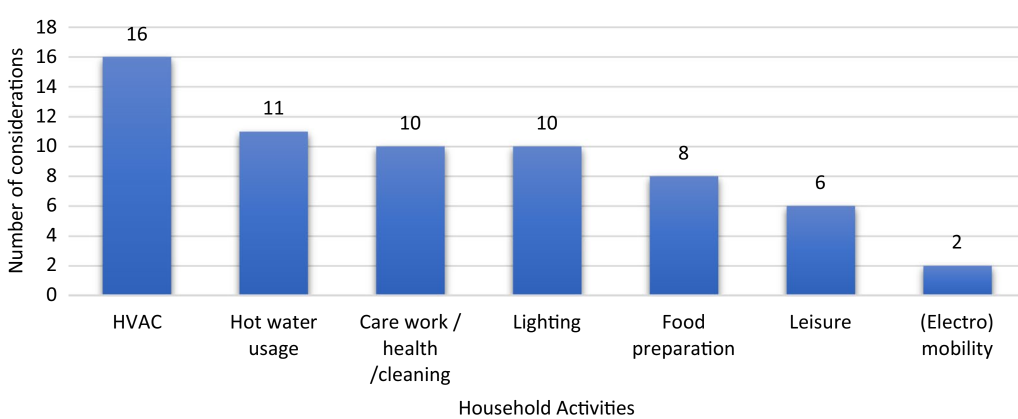

Fig. 5 Household tasks that were considered in the studies from the behaviour and social sciences (own figure). 'Care work' subsumes tasks related with, e.g., care for (elderly/young) household members; leisure was used as code for activities like watching tv or carrying out a hobby. The abbreviation HVAC refers to 'heating, ventilation and air conditioning'

modelling input (e.g., for the ABM in [35]) or as a basis for further surveys [41]. In combination with the inclusion of REs, however, the results show that the different operationalisation of behaviour at different steps of the LCA strongly influences its outcomes, and as expected so far mainly, but not exclusively, the use phase of SHTs.

So far, only a few explicit suggestions on how behaviour can be implemented in LCAs have been made, for example by Polizzi di Sorrentino et al. [26], Pohl et al. [29] and Suski et al. [82]. Polizzi di Sorrentino et al. [26] suggestions cover more general socio scientific, psychological and economic theories on decision processes and behaviours (see chapter: Analysis of the total number of articles) and name aspects for every LCA step which can be interconnected to the conception of user behaviours (e.g., "*decision context*, *system boundaries*, *functional unit*, *scenarios under assessment* and *assumptions on user behavior* [sic!]" for the GSD [26]). As these suggestions were criticized by Suski et al. [82] for still putting too much focus on the assessed product, they suggested a new practice focused LCA approach, picking up the general criticism by Pohl et al. [29] that there should be an increased awareness on use phase modelling in LCA.

As these approaches emphasize the importance of practices (at home), the results of this literature study support the findings from Pohl et al. [ibid.] that technology induced behaviour changes have so far been often strongly simplified in LCA studies. Attributional LCAs—like the ones analysed in this study—attempt, referring to the UNEP/SETAC Life Cycle Initiative [83], to "provide information on what portion of global burdens can be associated with a product (and its life cycle)". Compared to the methodological approaches applied in attributional LCAs, consequential LCAs "attempts to provide information on the environmental burdens occurring, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)" [ibid.]. Both attempts mainly influence the modelling of the LCI [ibid.]. Therefore, the choice of the approach can intercorrelate and with the operationalisation of behavioural effects, as different objectives are addressed and research questions can be tackled. This issue needs to be undertaken in future research.

On a further note, it can be argued that particularly within the context of (environmental) technology assessment as well as technology development, models and theories that incorporate the specific properties of technologies and their design are crucial—in addition to practice focused approaches suggested by Pohl et al. [29] and Suski et al. [82].

As shown in the results section diverse used methodological approaches can have effects on all different steps of the LCAs. For the studies analysed, behaviour was especially considered as important part of the FU and the scenarios that were assessed. Concerning the FU, which is defined as part of the GSD, it has to be noted, that it was especially the purchasing / equipment behaviour that was considered to be relevant. What is meant by this is, which type of smart home equipment (e.g., feedback screens, number of installed smart plugs or thermal sensors) was chosen by the users. It has to be distinguished, that this purchasing behaviour can be seen more as a beforehand decision, which can be used as input for the calculations on how average households might be equipped (as done by Pohl et al. [41]), rather than being part of the actual usage of a product which can be correlated to the change of household practices, habits and routines. The effects of the latter on the other hand are then more correlated with the environmental effects occurring, while a smart device is actually used. For the use phase Pohl et al. [41] found in their online survey no significant difference in heating behaviour / temperature setting, which correlates with the different environmental payback times that the ones found by Pohl et al. [41] and van Dam et al. [44], for instance.

Depending on the way how behaviour is incorporated into the LCI, it also influences the results of the LCA: considering different dimensions in which LCA results can be expressed, it becomes apparent, that in the regarded studies especially the dimension of time, e.g., in form of differences in environmental break-even points [42] or cumulated energy payback times are affected by the chosen approach to incorporate aspects of behaviour. According to the studies, the behaviour of people is correlating directly with the amount of time until the smart artefacts 'pay themselves off' in an environmental sense. Another behaviour dependent factor is the share of environmental impacts that are attributed to the different life cycle phases of the technology, in this case mainly correlated with the energy that is used and/ or saved on the behalf of the technology during its use phase. Correlating with the latter, the question of responsibility for the caused environmental impacts can be posed. Whereas in their result interpretations some studies conclude that the use phase accounts in the case of selected indicators for the largest shares of the environmental impacts [38, 44], other studies assign the largest share of environmental impacts to the production of the devices [39, 45]. These outcomes may also intercorrelate with the applied allocation of (by-) products, services etc. within an LCA (see, e.g., [84, 85] for an introduction on allocation principles) and cannot be presumed to solely depend on the chosen operationalisation approach.

Nevertheless, recommendations for the use of technical devices or even for the formulation of policies are often made on the basis of the results of LCAs (e.g., in [34] and [44]). The point of behaviour operationalisation (and thus on the 'input data' side of the LCA) should be critically reflected upon, particularly at this point, where the 'retranslation' of calculated ecological impacts into recommendations for action for people and society takes place (e.g., as done in [41]).

This review explicitly does not cover other methodological challenges next to behaviour operationalisation that can be encountered when conducting an LCA, the authors are aware of. As the interdisciplinary nature of the issues addressed already entails complex theoretical and practical considerations, reference is made here to current methodological literature on dealing with uncertainties [86, 87], prospectivity [88–90] or allocation principles [84, 85].

Household practices and users considered in LCA studies

As presented in the chapter Framing the users: specific habits, routines and practices, the socio scientific studies show a much more diverse picture of SHT related household activities, and therefore, influenceable behaviours than the LCA studies have paid tribute to, yet.

In general, the composition of the test groups and regarded user groups implies that non-Western lifestyles, which could be influenced differently by technologies like SHTs, but also offer other perspectives and livelihoods, have so far found few representations in the studies (Fig. 2). The data concerning gender and age representation (Fig. 3 and Fig. 4) should be seen as a tendency, as the lack of this information in many studies means that it is vague, how 'averages' or 'households' (to whose are referred to in other studies like in [91, 92] or [93]) are made up and whose realities of life and technology adaptations are actually represented. However, the lack of the provision of this data should also be viewed critically, as this important information could affect the transferability and validity of the study results (as explained in the results chapter), is missing.

Concerning the representation of different behaviours and household activities that can be influenced by SHTs, a strong focus of LCAs on heating behaviour and the overall energy demand of households was found. As heating is only one practice example, the inflexibility of performing household tasks was specifically addressed, e.g., also by Nicholls & Strengers [80] with a focus on households with children. They argue that, especially in households with (small) children, "*bundles*" of certain practices which are commonly executed by more than one family member, are performed usually at a certain time of the day. This interweaving of different household practices, they state further, can contribute to make the shifting of peak times difficult, with the latter being one of the main goals of DSM and the introduction of SHTs. Hagejärd et al. [81] also identified factors preventing the timely shifting of household practices, of which a "*lack of flexibility in everyday life*" also accounts as one of the main factors. These findings do not only again demonstrate the misconception of the rational and price led consumer, whose consumption can be influenced by eliminating an information deficit by the use of smart technologies, but also the individuality of household organisation, depending on the configuration of household members. Contrasting these findings against considered practices in LCA studies, it has to be noted that in the latter a strong emphasis on HVAC behaviour can be found, with all 10 studies discussing or assessing the impacts of the energy demand needed for heating.

This finding was accompanied by the exclusion of other activities and in particular changes of behaviour by most of the research scopes of the LCA studies. This not only creates gaps in the translation of existing information into the LCA models, but also results in a poorer transferability of LCA results. Certainly, a specific focus choice in LCA studies can be justified and explained by the need of defining strict boundaries—nevertheless, this approach has the potential to neglect environmental effects which are triggered by behaviour influenced by SHTs other than HVAC. Another phenomenon to be observed is that the use of household appliances requiring electricity is usually subsumed under the total electricity consumption of a household in the LCA studies. The overall energy consumption (i.e., power and heat) on the household level in these studies is interpreted as a result of inhabitants' behaviour, or even treated as being synonymous. The background to this result is that the link between domestic activities and practices (which Madsen & Gram-Hanssen [94], for example, also refers to as *home making*) and the corresponding energy consumption is apparently under-discussed in LCA studies. Depending on the scope of the study, it can be argued that total energy consumption is one of or even the most decisive factor for calculating environmental impacts. Presumed technology induced behaviour changes are in the step of composing the LCI translated into reductions of the overall energy consumption, making it the crucial step of data and information transformation. Due to the decoupling of the triggers (changes of practices and home making activities) and the impacts as well as the focus on the impact level, underlying household dynamics remain under-discussed.

As already stated in the subchapter 3. Category: averages and assumptions, this usually takes the form of using average values. It was found though, that it is neither implicitly deducible nor explicitly emphasised which 'average' behaviours are responsible for the development of the average values in the first place. This is interesting in light of the fact that a change of behaviours (usually not defined in more detail) is assumed for the illustration and development of use phase scenarios, which would lead to a synonymous reduction in energy consumption. At this point, it can be argued that the environmental impact of electricity does on the generation side not depend on what it is used for, but on how it is generated. However, as soon as the aim is to use an LCA study to depict the reality as accurately as possible or to derive (behaviour or policy) recommendations from the technology assessment, it is necessary to understand which household practices can actually potentially be changed. Based on our results, it can be argued that too little attention is paid to the practices and partially resolved consumption data lying behind the calculation of the average values used in LCA studies. Focussing stronger on the methodological challenges and the effects of the usage of average consumption data, our results are in line with the criticism expressed by St-Jacques et al. [95], based on their research. In their study they have also shown the impact that the use of average values can have on the calculation of GHG-emissions—according to their research an overestimation of the actual building related GHG-emissions. The understanding of the relationship between household activities and their contribution to average data is, therefore, not only necessary for comprehending and assessing individual environmental impacts of single households, but also crucial when looking at the bigger picture of larger (smart) grids and, e.g., country scales.

Further perceptions and propositions

In this section further thoughts and contextualization are presented, that can be derived from the interdisciplinary scope of this literature study, leading to further drawn recommendations presented in the following chapter.

The results of the literature study show that there are still major challenges to be faced regarding the representation of socio-ecological interdependencies, in this case against the background of the environmental effects of SHTs. These can be particularly derived from the diversity of social preconditions for technology usage (e.g., concerning the sociodemographic backgrounds of users) and from the heterogeneity of possible behavioural changes. To identify environmental effects using the LCA methodology, the abstraction of information (and thus also the simplification of complex cause–effect relations) is always a necessary step in experiments and modelling studies. This process constantly requires decisions about setting reasonable system boundaries by including or excluding certain aspects of reality. When recognizing the importance of behaviours for the calculations of environmental impacts of SHTs, the LCA methodology still poses the challenge to quantify effects caused by behavioural changes.

Concerning the level of abstraction with regard to different information necessarily handled in LCA studies, the works from Andrianse [75] and Linser [96] show the processing of data, information and indicators to indices in relationship to their level of aggregation. More specifically, they illustrate how data is aggregated and to a certain extent, 'sharpened', to make phenomena from the real world depictable, quantifiable and interpretable. It can be argued that in the case of behaviour depiction and operationalisation in most of the analysed studies the abstraction level increases from more experiment and data driven approaches in the social and behaviour sciences to the indicator level in LCA studies. Most studies on behavioural changes of people in interactions with technologies often generate a very wide variety of information, including qualitative and, above all, especially descriptive data.

This necessary step of abstraction should not initially be seen as inherently critical—however, as being depicted, it goes along with the danger of losing valuable information from the less aggregated data types, as the abstraction level increases. Considering this issue, as soon as recommendations and conclusions for actions in reality are derived from indicators, this increased abstraction level should be considered more closely. In addition, it can call for a greater awareness of which information (in this case, for example, on the significance of routines or the realities of people's lives) are actually aggregated.

If, in the interpretation step of the LCA, calls for changes in behaviour on the basis of LCA data or especially recommendations for policies and the designs of products are derived, these steps should be taken with caution. In the interpretation phase of the LCA the results generated in indicator form are often reconnected to real life problems (as product design or policies or the choice of a specific technology configuration), making the step even more crucial, when LCA results are used as a base for decision making, which has also been criticized, e.g., by Suski et al. [82]. Based on the findings of this literature study it becomes apparent that a greater awareness for the necessary abstraction process could contribute to an enhanced modelling process, but especially a more conclusive and reliable interpretation of the LCA results. As LCAs are often used as decision support, it can also be reasoned that a deeper acknowledgement of the abstraction levels dealt with in the LCAs could improve its meaningfulness.

One aspect only marginally addressed so far in this study is the data access for LCA studies that slightly goes along with the discussed abstraction levels. Three main approaches (literature, databases and own surveys) were identified in the studies for the gathering of data and information which were then primarily used to generate theoretically substantiated load profiles or savings scenarios. The term behaviour in these cases mostly referred to the sequence of (household) devices usage over a certain period of time, resulting in an energy usage that could be recorded by the smart metering devices. However, as this approach is still based on the quasi-equation of 'energy consumption' and 'behaviour', other approaches should also be discussed. Even if the data collection can become comparatively time-consuming, greater involvement of stakeholders could generally improve the validity of LCA studies of SHTs and other (smart) information and communication technologies. Similar to the approach chosen by Pohl et al. [40], this could take the form of surveys, but, furthermore, of (qualitative) interviews. Broad recognition and practical testing of the practice-orientated methodological procedures proposed by Suski et al. [82] could also increase the informative value of LCAs and improve its meaningfulness in decision contexts.

Recommendations

Summing up the results of this interdisciplinary literature study, different recommendations can be derived. Some of these relate more to the general implementation of the LCA standards, others to the handling of behaviour, activities, routines etc. in the latter.

Operationalisation of behaviour in LCA

- The ISO norms for the conduction of an LCA [24, 25] request transparent reporting. It has to be noted that in not all LCA studies were the different steps (especially the FU and the applied LCIA methods) and data inputs clearly described. This also leads to an incomparableness of LCA outcomes and uncertainties with regard to drawing conclusions from the overall results. Therefore, an emphasis in future LCAs on SHTs should be put on an accurate documentation and communication of the different LCA steps with their assumptions and limitations.
- In addition to individual energy savings potentials, which are to be achieved with the help of SHTs on household levels, DSM at the energy system level is primarily aimed at peak shaving in the electricity grid and balancing generation and consumption. This aspect has not yet been sufficiently addressed, as individual SHTs could cause different environmental impacts on the system level compared to the household level.
- With regard to the representation of users, most LCA studies to date have primarily used average energy consumptions as use parameters [26, 27]. However, since divergent lifestyles cannot be represented by single averages, e.g., different baseline scenarios could be a first attempt to represent different energy usages already in the LCI step of the LCA. To improve the visibility and representation of different user groups, diverse household and family structures (households with children or elderly people, singles, couples, shared flats, non-heteronormative relationships etc.) could increase the representativeness of LCA results.
- Referring again to the accounting of behavioural effects, there was a strong focus on the consideration of REs, which are subsequent or parallel effects of technology usages. Approaches such as those of Pohl et al. [29] could offer an initial approach to better illustrate instead or additionally the direct effects of the technology use to counteract the equalization of behaviour and energy consumption.
- When generating scenarios for an LCA, there should be a greater acknowledgement of the actual (in-)flexibility of different household activities. For future LCA studies, the consideration of 'activity clusters' or 'bundles' (comp. [80]) could, therefore, be an approach for an improved and more authentic representation of user behaviour.
- Smart meters can record actual energy usage data. These could offer a starting point for more individualised baseline scenarios for LCAs of SHTs. If it is not possible to conduct own measurements, these could be taken from the literature, as, e.g., Issi & Kaplan [97] used smart meters for the identification of energy load profiles as well as Gajowniczek & Zabkowski [98] and Wen et al. [99] for use pattern identification.

Interdisciplinary cooperation and data transfer

- There should be a greater awareness for the abstraction level of the LCA methodology and the information losses that necessarily go along with it as LCA studies can be subjected to different kinds of necessary pragmatic decision-making processes. Generalising statements or the formulation of policy recommendations should be derived with greater care or backed up/supported by stakeholder involvement.

- Furthermore, the need for closer cooperation between social sciences and LCA practitioners can be formulated. In terms of implementation, the following ideas could be initial approaches:
- GSD: formulation of an interdisciplinary approved study scope with regard to the inclusion and representation of different user groups concerning their reality of life, as well as life styles and technology adoption.
- LCI: Use and development of interdisciplinary research methods (surveys, interview formats), through which the scope of the study can be addressed accordingly.
- LCIA: Identification of interactions critical for environmental impacts and corresponding usage behaviour; potentially more accurate representation of environmental impacts which can be influenced by different user behaviour (changes in household practices, disposal, …) in the different life cycle phases of a technology.
- Interpretation: Formulation of policies, design and utilisation recommendations based on an improved data basis and combining findings from the various disciplines, respectively.

Conclusions

As SHTs are supposed to enable future DSM strategies to ensure the balancing of energy supply and demand a comprehensive understanding of correlating environmental and social impacts of these technologies is necessary. Since the LCA methodology that is often applied for the assessment of environmental effects of products, does not yet specify the consideration of user behaviour and related effects, this study identified how behaviour has been operationalised with which effects in LCA studies of SHTs up to date. In addition, it was analysed how insights from behaviour and socio scientific studies on the influences of SHTs on users were represented and negotiated in the corresponding LCA studies.

The results of this literature study show the necessity for a better understanding of behaviour operationalisation in LCAs when deriving recommendations for policy making, design decisions and usage behaviour for consumers. The identified main approaches for operationalising behaviour in LCA studies (1. behaviour theory-based approaches, 2. use of models and (literature-based) deductions and 3. averages and assumptions) correlate with the results of the LCA, leading to incomparable and even contradicting results concerning the environmental impacts of SHTs. It was also shown that findings from the social sciences on practices and household activities were only partially incorporated into the environmental technology assessment and methodologically challenging, which often led to a very selective consideration of behavioural effects with a strong focus on HVAC behaviour. The results, therefore, emphasize the articulated needs for improved methodological approaches for example from Pohl et al. [40] as well as Suski et al. [82].

As the literature study was limited to the specific case of SHTs and their environmental impacts, some results might not be generalisable for LCA studies. Nevertheless, the results can contribute to the development of enhanced modelling and inclusion approaches of behavioural aspects into LCAs in the future. As a better understanding of how the different approaches influence the LCA results was developed, data transfer between scientific disciplines and data adaptions should in the future happen under an enhanced acknowledgement of the information losses that inevitably occur. In conclusion, a need for greater interdisciplinary cooperation when it comes to assessing and evaluating socio-ecological interactions and impacts can be derived from the results of this literature study. This cooperation could improve the validity and also the robustness of LCA studies, but also in reverse provide insights on actual environmental effects of (incentivised) behaviours or changes of the latter, respectively.

Abbreviations

ABM	Agent based modelling
ADP	Abiotic depletion potential
CED	Cumulative energy demand
DSM	Demand side management
EI	Environmental impacts
GSD	Goal and scope definition
GWP	Global warming potential
HEMS	Home energy management system
HTTP	100 human toxicity potential (regarded over a time span of 100 years)
HVAC	Heating, ventilation & air conditioning
ICT	Information and communication technologies
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MD	Metal depletion
PED	Primary energy demand
RE	Rebound effect
SHT	Smart home technology

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-024-00506-8.

Additional file 1

Acknowledgements
MT would like to thank her supervisors for their support, assistance and ongoing encouragement. Also, we would like to thank Lesley Tohill for the revision of the manuscript.

Author contributions
MT: paper conceptualisation, literature analysis, methodology, writing of the original draft, graphs, review & editing. HW and UBD: review and editing. TV: review and supervision.

Funding
Open Access funding enabled and organized by Projekt DEAL. This research was financed the DLR-internal project NaGsys, which was funded by the Helmholtz Association's Energy System Design research program.

Availability of data and materials
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Received: 28 March 2024 Accepted: 26 December 2024
Published online: 09 January 2025

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