Integration of Higher-Order Effects into Life Cycle Assessment of Information and Communication Technology

vorgelegt von

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Abstract

The application of information and communication technology (ICT) is attributed a decisive role in the necessary reduction of energy and resource demand and associated environmental emissions. However, a closer look at the environmental impact of ICT reveals a contradictory picture: On the one hand, the application of ICT has the potential to reduce environmental impacts and counter climate change. On the other hand, ICT's direct energy and resource demands and their associated environmental impact are substantial. So far, it has not been possible to determine the actual environmental impact of various ICT applications. This is due to the lack of suitable approaches to include higher-order effects such as induction and rebound effects in the life cycle assessment (LCA) of ICT. This thesis aims at addressing this gap.

With a focus on the application of ICT, this thesis therefore investigates how higher-order effects can be integrated into LCA of ICT. Higher-order effects of ICT are those that stem from the application of ICT, for example optimisation, induction or rebound effects. Three research questions were formulated for this purpose. The first was based on a literature review and identified the various challenges of including higher-order environmental effects of ICT into LCA. These challenges included methodological issues with regard to the definition of goal and scope in LCA of ICT, and the lack of empirical data on use-related higher-order effects. Based on these challenges, the second research question considered how higher-order effects can be properly addressed in the goal and scope definition in LCA. To this end, a conceptual framework *The user perspective in LCA* was developed that firstly outlines various user-driven parameters, such as number and choice of products or intensification of use, and secondly relates these parameters to corresponding LCA modelling characteristics, such as definition of functional unit or system boundaries. Finally, the third research question focused on the operationalisation of the conceptual framework and its application in two case studies. The case of smart homes with smart heating in Germany was used to demonstrate the feasibility of the framework and to gain insights into the environmental assessment of smart home systems (SHS) when higher-order effects are also captured.

The study design included the operationalisation of the user-driven parameters, the collection of primary data using an online survey, and the environmental assessment with LCA both of the average SHS in Germany (first case study), and of 375 different SHS in Germany (second case study). For one, findings show that direct environmental effects of the SHS are substantial. For example, heating optimisation in the average SHS must be

at least 6% of the annual heating energy demand over three years in order to balance out the effects of the production and operation of the SHS for the impact categories Climate Change and Primary Energy Demand. Secondly, it was found that user behaviour in the smart home varies greatly and that both the choice of device (induction effect) and the actual heating behaviour (rebound effect) have a decisive influence on the overall environmental performance of the SHS. It follows that the inclusion of user behaviour in LCA of ICT can increase the uncertainty of the results if the data on user behaviour are not appropriately validated. With regard to LCA modelling, it was found that a proper definition of the functional unit is particularly relevant for the integration of higher-order effects into the goal and scope definition. Another challenge can be the handling of multifunctionality when it comes to the inclusion of induction effects.

With the development of the conceptual framework *The user perspective in LCA* and its operationalisation and application to the case of smart homes, this research presented a novel approach to integrating higher-order effects into LCA of ICT. This is particularly relevant when investigating the environmental net saving potential of the application of ICT. Future research can tie in with this, for example in the investigation of higher-order ICT effects in other sectors, in the development of further interdisciplinary approaches for investigating product use behaviour, or in the development of databases with representative behavioural data for product assessment.

Zusammenfassung

Der Verwendung von Informations- und Kommunikationstechnologie (IKT) wird bei der notwendigen Reduktion von Energie und Ressourcen und den damit verbundenen Umweltauswirkungen eine entscheidende Rolle zugeschrieben. Ein differenzierter Blick auf die Umweltauswirkungen lässt allerdings ein widersprüchliches Bild erkennen: Einerseits kann der Einsatz von IKT in anderen Prozessen und Sektoren Umweltbelastungen reduzieren und dem Klimawandel entgegenwirken. Andererseits sind der direkte Energie- und Ressourcenbedarf der IKT und die damit verbundenen Umweltauswirkungen erheblich. Bislang war es nicht ohne weiteres möglich, die tatsächlichen Umweltauswirkungen verschiedener IKT-Anwendungen zu ermitteln, da es an geeigneten Ansätzen fehlt, um übergeordnete Effekte wie Induktions- und Reboundeffekte, die sich aus der Anwendung der IKT ergeben, in die Ökobilanz einzubeziehen. Diese Lücke schließt die vorliegende Arbeit.

Mit dem Fokus auf die Anwendung von IKT wird untersucht, wie übergeordnete Umwelteffekte in die Ökobilanz von IKT integriert werden können. Als übergeordnete Effekte werden diejenigen Effekte bezeichnet, die durch die Anwendung der IKT entstehen, beispielsweise Optimierung, Induktion, oder auch Rebound. Für die Untersuchung werden drei Forschungsfragen formuliert. Die erste bezieht sich auf die aktuellen Herausforderungen bei der Einbeziehung von übergeordneten IKT-Effekten in die Ökobilanz. Auf der Grundlage einer Literaturrecherche werden verschiedene dieser Herausforderungen identifiziert, beispielsweise methodische Herausforderungen in Bezug auf die Definition von Ziel und Untersuchungsumfang in der Ökobilanz von IKT oder der Mangel an empirischen Daten zu nutzungsbezogenen Effekten. Auf der Grundlage dieser identifizierten Herausforderungen fokussiert die zweite Forschungsfrage darauf, wie die übergeordneten Effekte bei der Definition von Ziel und Untersuchungsrahmen in der Ökobilanz entsprechend berücksichtigt werden können. Dafür wird das Framework *Die Nutzerperspektive in der Ökobilanz* entwickelt. Darin sind verschiedene nutzergesteuerte Parameter wie Anzahl der Produkte oder die Nutzungsintensität aufgeführt und den entsprechenden Eigenschaften in der Ökobilanz, wie der Definition der funktionalen Einheit und der Systemgrenzen zugeordnet. Die dritte Forschungsfrage konzentriert sich auf die Operationalisierung des Frameworks und dessen Anwendung in zwei Fallstudien. Als Anwendungsfall wird das Smart Home mit smarter Heizungssteuerung in Deutschland verwendet. Ziel ist es, die Machbarkeit des Frameworks zu demonstrieren und Einblicke in die Umweltbewertung von Smart Homes zu gewinnen, wenn auch übergeordnete Effekte erfasst werden.

Das Studiendesign umfasst die Operationalisierung der nutzergesteuerten Parameter, die

Erhebung von Primärdaten mittels einer Online-Befragung und die Umweltbewertung des durchschnittlichen Smart Homes (Fallstudie 1), sowie von 375 verschiedenen Smart Homes in Deutschland (Fallstudie 2). Die Ergebnisse verdeutlichen zum einen die erheblichen direkten Umweltauswirkungen von Smart Homes. Um die Auswirkungen aus der Produktion und dem Betrieb des Smart Homes in den Wirkungskategorien Treibhauspotential und Primärenergieverbrauch auszugleichen, muss beispielsweise durchschnittlich mindestens 6% des jährlichen Heizenergiebedarfs über drei Jahre durch Optimierung des Heizenergieverbrauchs eingespart werden. Zum anderen wurde festgestellt, dass das Nutzungsverhalten im Smart Home sehr unterschiedlich ist und sowohl die Wahl der Geräte (Induktionseffekt) als auch das tatsächliche Heizverhalten (Rebound-Effekt) einen entscheidenden Einfluss auf die Gesamtumweltbewertung des Smart Homes ausüben. Daraus folgt, dass die Einbeziehung des Nutzerverhaltens in die Ökobilanz von IKT die Unsicherheit der Resultate erhöhen kann, wenn diese nutzerspezifischen Daten nicht angemessen validiert werden. Für die Modellierung von übergeordneten Effekten in der Ökobilanz zeigen die Ergebnisse, dass eine korrekte Definition der funktionalen Einheit besonders wichtig ist. Eine Herausforderung kann der Umgang mit Multifunktionalität sein, wenn es um die Einbeziehung von Induktionseffekten geht.

Mit der Entwicklung des Frameworks *Die Nutzerperspektive in der Ökobilanz* und dessen Operationalisierung und Anwendung am Beispiel von Smart Homes präsentiert diese Forschung somit einen neuartigen Ansatz zur Integration von übergeordneten Effekten in die Ökobilanz von IKT. Dies ist insbesondere bei der Untersuchung des Umwelteinsparpotenzials von IKT-Anwendung von Bedeutung. Daran können zukünftige Forschungsarbeiten anknüpfen, beispielsweise bei der Untersuchung des Einsparpotentials von IKT in anderen Sektoren, bei der Entwicklung von weiteren interdisziplinären Ansätzen zur Untersuchung von Produktnutzungsverhalten, oder auch bei der Entwicklung von Datenbanken mit repräsentativen Nutzungsdaten für die Produktbewertung.

List of core publications

Publication 1:

Pohl, J., Hilty, L.M., Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches. Journal of Cleaner Production 219, 698–712. https://doi.org/10.1016/j.jclepro.2019.02.018

Publication 2:

Pohl, J., Frick, V., Höfner, A., Santarius, T., Finkbeiner, M., 2021. Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home? Journal of Cleaner Production 312, 127845. https://doi.org/10.1016/j.jclepro.2021.127845

Publication 3:

Pohl, J., Frick, V., Finkbeiner, M., Santarius, T., 2022. Assessing the environmental performance of ICT-based services: Does user behaviour make all the difference? Sustainable Production and consumption 31, 828–838. https://doi.org/10.1016/j.spc.2022.04.003

List of abbreviations

ADP .... Abiotic Depletion Potential

Ecotox .... Ecotoxicity

EoL .... End of Life

ETSI .... European Telecommunication Standards Institute

GHG .... Greenhouse gas

GWP .... Climate Change

IC .... Integrated Circuit

ICT .... Information and communication technology

IEA .... International Energy Agency

ILCD .... International Reference Life Cycle Data System

LCA .... Life Cycle Assessment

MDP .... Metal Depletion Potential

PCB .... Printed circuit board

PED .... Primary Energy Demand

PSS .... Product/Service-System

PWB .... Printed wiring board

SHS .... Smart home system

Contents

1 Introduction

Society and the economy are in the midst of an epochal change driven by the necessary sectoral transformations to ensure a good life for all within planetary boundaries (Rockström et al., 2009). The use of information and communication technology (ICT) plays a decisive role in this transformation in multiple ways (Andersen et al., 2021): On the one hand, ICT's direct energy and resource demands and associated environmental impacts are substantial (Belkhir and Elmeligi, 2018; Freitag et al., 2021; Van Heddeghem et al., 2014). On the other hand, the application of ICT in other processes and sectors is intended to reduce environmental impacts and counter climate change (Mickoleit, 2010). Examples range from the virtualisation of physical goods (e.g. video streaming, Shehabi et al., 2014), to digital process monitoring & control, (e.g. in smart production, Yang et al., 2019), and forms of remote work (e.g. using videoconferencing, Shabanpour et al., 2018), to new modes of consumption, such as the sharing of products organised via digital platforms (Amatuni et al., 2020). This means that, under certain conditions, ICT can help to alleviate existing environmental problems and thus contribute to the necessary sustainability transformation.

There are an increasing number of studies on the environmental effects of the application of ICT in various sectors such as food, housing, mobility or consumption (see for example recent literature reviews on the topic by Court and Sorrell, 2020; Mulrow et al., 2022; or Wilson et al., 2020). However, it is not yet possible to draw general conclusions regarding the environmental impact of these various applications of ICT from the available study results. This is because most studies only incompletely capture the environmentally relevant effects (Horner et al., 2016). Mostly, only the energy and resource demand along the life cycle of ICT hardware is taken into account. However, interdependencies between the user and the technical system are often overlooked, though they also influence the realisation of the technical savings potential of ICT at the application level. Besides variances in user behaviour (Horner et al., 2016), these include for example forms of user adoption (Hargreaves et al., 2018), or the shift towards a more energy-intense lifestyle (Tirado Herrero et al., 2018). As a result, if use-specific effects are not included, there is a systematic overestimation of the realistic saving potentials of ICT (Arvesen et al., 2011). Furthermore, at the macroeconomic level, there are other, partly countervailing effects such as sectoral change or economic growth that must also be taken into account when estimating the overall energy and resource demand of ICT (Lange et al., 2020).

This thesis focuses on the environmental assessment of ICT at the application level. The aim is to contribute to further understanding at the theoretical, methodological and empirical levels, of the various effects of ICT on energy and resource consumption and the resulting environmental impacts.

This chapter first presents the state of research on the environmental effects of ICT, and their assessment using life cycle assessment (LCA) in general and the example of smart homes in particular (Section 1.1). In Section 1.2, research gaps and challenges are derived. The aim and structure of the thesis are presented in Section 1.3.

1.1 State of research

This section illustrates the background and motivation of this thesis by presenting the state of research divided in three topics: the environmental effects of ICT, their assessment with ICT, and smart homes as an example of the application of ICT in the residential sector.

1.1.1 Environmental effects of ICT

For more than two decades, the impact of ICT on society and the environment has been the subject of public and scientific debate. On a functional level, ICT enables the collection, processing, storage, transmission and output of data and can thus provide a multitude of services in various sectors. In the following, these are summarised with the term *ICT-based services*. Great hopes are being pinned on ICT-based services for saving resources and energy (Hilty et al., 2006; Mickoleit, 2010), or for climate change mitigation (Kaack et al., 2022; Sui and Rejeski, 2002). In addition, the role of ICT-based services in environmental monitoring, including biodiversity (Proença et al., 2017; Silvestro et al., 2022), air quality (Schaefer et al., 2020) or water quality (Park et al., 2020) is highlighted. Yet there is also criticism of the environmental impact of ICT through the production, use and disposal of ICT hardware (Arvesen et al., 2011; Borning et al., 2018; Murugesan, 2008). Attention is also drawn to the role of consumption-increasing effects such as rebound effects in the overall environmental impact of ICT-based services, which counteract potential efficiency gains (Galvin, 2015; Horner et al., 2016; Plepys, 2002).

The *framework of environmental effects*, proposed by Berkhout and Hertin, 2004, and advanced by for example Hilty and Aebischer, 2015, or Horner et al., 2016 captures and describes the complex, partly counteracting environmental effects of ICT on several layers (see Figure 1):

Direct effects result from the energy and resources required to produce, operate and dispose of end-user devices, communication networks and data centres. They thus contribute to increasing resource use.

A literature review comparing LCA studies of various ICT products (Arushanyan et al., 2014) concludes that, depending on the device type and impact category, either the production phase or operational phase is the most impactful life cycle phase. The production of electronic components, e.g. integrated circuits (IC), printed wiring boards (PWB), or displays, contributes most to the environmental impact of the production phase, e.g. of smartphones, tablets, or desktop PCs (Clément et al., 2020; Teehan and Kandlikar, 2012). For the provision of an ICT-based service, usually both end-user devices and ICT infrastructure are involved. For the example of video streaming, Schien et al., 2021 show that the devices in the household, and not ICT infrastructure, are responsible for most of the electricity demand. However, it must be pointed out that the calculation of direct effects is accompanied by great uncertainties due to the low availability of up-to-date inventory data, inconsistent modelling approaches and a lack of transparency (Arushanyan et al., 2014).

Indirect effects result from the application of ICT-based services in other sectors and contribute to decreasing (through optimisation or substitution effects) or increasing resource use (through rebound and induction effects).

Optimisation (i.e. improved efficiency) and substitution (i.e. replacement of physical products by their digital equivalents) aim to improve resource efficiencies of processes from a technical point of view. For example, according to Urban et al., 2016, optimisation effects through connected thermostats in the home can account for a reduction of up to 10% of overall household heating energy demand. As another example, for the substitution of in-person meetings with videoconferencing, Coroamă et al., 2012 show a reduction of up to 50% of travel-related greenhouse gas (GHG) emissions by organising a conference in two locations in parallel and connecting the two venues with videoconferencing technology.

By changing consumption patterns via the increased use of ICT-based services, optimisation and substitution effects can also be partially compensated. Rebound effects are directly attributable to efficiency gains due to the use of ICT-based services, e.g. with regard to money, time or space (Börjesson Rivera et al., 2014), or, when applying psychological mechanisms, with regards to motivation (Santarius and Soland, 2018). See Sorrell, 2007 for a general introduction to the topic. For instance, a study of the effects of telework indicates a rebound effect of 14-73%, manifesting in increased travel for other purposes (Jørgensen et al., 2006). Hilty and Bieser, 2017 assume rebound effects of 4-37% for various ICT-based services attributed to time and cost reductions. Induction effects can be traced back to an increased choice of options that come with the introduction of ICT (Walnum and Andrae, 2016). This can refer to both choice of products or increased use time, without a causal increase in efficiency taking place. Although the rebound effect in particular is well described in theory, sufficient empirical data on the actual level of rebound and induction effects of ICT-based services is still lacking. It follows that the net environmental effects of ICT-based services can only be quantified very imprecisely because, as several authors have argued, they are particularly susceptible to high rebound effects (Galvin, 2015; Hilty and Aebischer, 2015; Walnum and Andrae, 2016).

Systemic effects result from the deployment of ICT at the macroeconomic level and also contribute to decreasing (through sustainable lifestyles or sectoral change), or increasing resource use (through rebound effects or economic growth). See for example Lange et al., 2020 for an investigation of the effects of ICT on electricity consumption from a macroeconomic perspective.

Since the classification between the different layers is not distinct in the literature (see for example Horner et al., 2016 for a comparison of the different taxonomies of ICT effects), indirect and systemic effects are summarised in the following under the term *higher-order effects*.

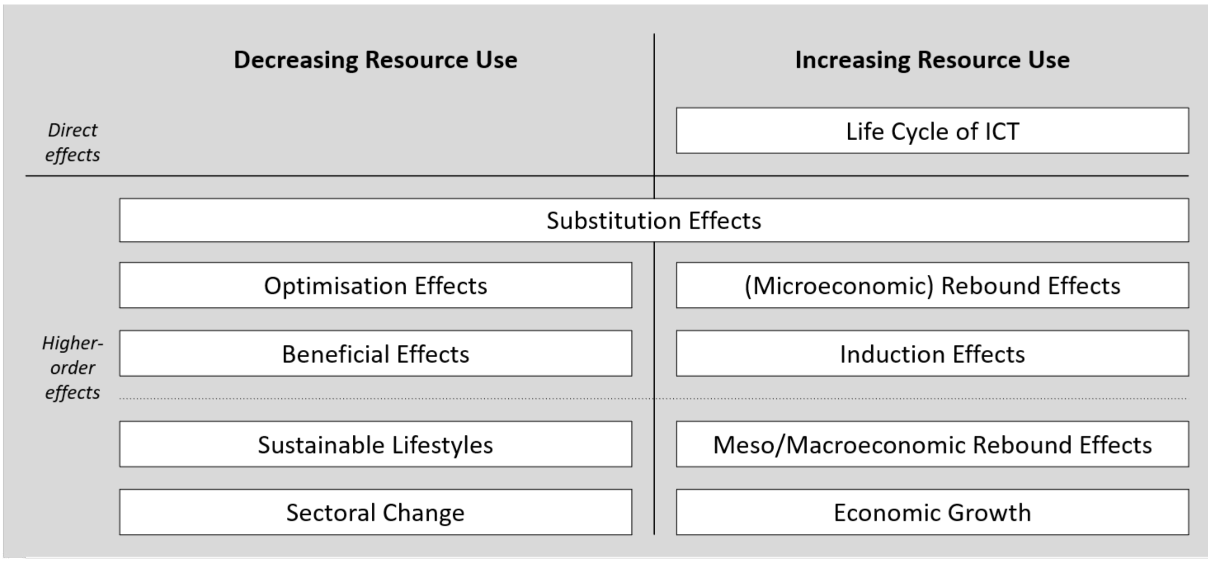

Figure 1: Environmental Effects of ICT, based on Hilty and Aebischer, 2015; Lange et al., 2020; Pohl et al., 2019a.

In summary, whether or not ICT-based services contribute to the reduction of energy and resource demand depends first on how the ICT-induced savings relate to the expenditures along the life cycle of ICT hardware and the changes in use patterns in certain impact categories, and second on whether burden shifting occurs between different impact categories.

1.1.2 Assessing the environmental effects of ICT with LCA

LCA has been used to assess the environmental effects of ICT for almost three decades (Hischier et al., 2015). Initially applied mainly in the electronics industry, environmental assessment of ICT has also been the subject of research for some time (Itten et al., 2020). There are numerous studies on direct effects of ICT devices such as computers, laptops, TVs or mobile phones, as shown in a literature review by Arushanyan et al., 2014. However, LCA of ICT products is very complex (Moberg et al., 2014) and some methodological and data availability challenges have arisen that have not yet been resolved. These challenges relate to decisions regarding goal and scope definition (e.g. definition of system boundaries, time scope, geographical scope, types of impacts chosen, Arushanyan et al., 2014; Capelleveen et al., 2018), and data inventories (e.g. lack of up-to-date data on supply chain, use, disposal, outdated inventory data sets, lack of generic data sets on ICT products, Clément et al., 2020; Court and Sorrell, 2020; Moberg et al., 2014). There is a standard for the assessment of ICT products based on ISO 14040, 2006 and ISO 14044, 2006 developed by the European Telecommunication Standards Institute (ETSI) (ETSI EE, 2015). However, to the knowledge of the author of this thesis, the ETSI standard is rarely used in scientific practice.

With the growing interest in the potential of ICT to reduce environmental impact, ICT-based services and their mitigation potential are also increasingly being studied. This means that, in addition to direct effects, the scope of the investigation also extends to the higher-order effects of ICT. Recently, proposals have been developed to extend the ETSI standard to include the higher-order effects of both ICT-based single services (Coroamă et al., 2020) and ICT-based multiple services (Bergmark et al., 2020). However, due to the most recent publication date, these recommendations are not used in practice yet. Literature reviews by Bull and Kozak, 2014; Horner et al., 2016; and Mulrow et al., 2022 point out further challenges related to LCA methodology, such as the consistent definition of system boundaries and functional units, or the handling of multifunctionality. Coroamă et al., 2020 point to another issue with regard to the definition of goal and scope, namely that much of the research on the higher-order effects of ICT focuses exclusively on mitigation effects (e.g. optimisation and substitution) and ignores the possible consumption-enhancing effects (e.g. rebound, induction). Horner et al., 2016 attribute this to the rather technical nature of these studies and to a general lack of behavioural data, and call for a stronger integration of especially use-related higher-order effects of ICT into environmental assessments. This is necessary because otherwise the net savings potential of ICT-enabled services could be overestimated (Arvesen et al., 2011).

The question of whether or not higher-order effects should be included in the LCA of ICT depends thus on the overall objective of the study. With regard to the framework of the environmental effects of ICT, the objective can differ depending on whether the focus is on the environmental effects along the life cycle of ICT devices, their technical performance, or whether the environmental effects of ICT-based services are to be investigated (i.e. the "ICT-induced effects", as defined by Coroamă et al., 2020). Thus, only in the latter case are issues involved that require the integration of higher-order effects into the modelling.

Detached from the framework of environmental effects, the inclusion of higher-order effects helps with including variances in user/consumer behaviour related to products or services in LCA. Again, depending on the objective of the study, this can be done in different ways, e.g. by including variances in user behaviour as a boundary condition or as part of use phase modelling in product-centred approaches, or by focusing on different types of consumption behaviour (i.e., in consumption-based approaches). As defined in ISO 14040, 2006, the product focus is central to LCA. However, when referring to a person or a household in the functional unit, the environmental impact of the product life cycle is allocated to the user (Sala et al., 2019), thus shifting the focus from producer to consumer.

Irrespective of the ICT use case, there has been a general debate for some time about the consideration of variances in user behaviour in LCA. In many studies, variances in user behaviour, such as different usage patterns, user-product interactions or rebound effects are often insufficiently captured (Pohl et al., 2019b). This can affect the validity of assessment results (Ross and Cheah, 2017) and is described as one of the major gaps in LCA (Hellweg and Milà i Canals, 2014; Miller and Keoleian, 2015; Suski et al., 2021). When integrating variations in use phase modelling in LCA, assumptions are usually made about product handling, frequency and duration of use, sometimes backed up by previous research or statistics (Daae and Boks, 2015). When it comes to the inclusion of user behaviour, the use phase is often explicitly mentioned as a relevant part of LCA modelling. However, Polizzi di Sorrentino et al., 2016 show from a behavioural science perspective that behavioural aspects also include product choice or the context of use. Thus, in this context, besides use phase modelling, also definition of system boundaries, product systems or reference systems are relevant in LCA.

There are a number of suggestions on how to put the inclusion of user behaviour in LCA on a more scientifically sound basis. Zimek et al., 2019 point out that by expanding the scope of LCA, user behaviour can be addressed more precisely. To better describe the uncertainty of results due to different user behaviour, additional statistical methods could be applied (Ross and Cheah, 2017). For the integration of rebound effects in LCA, Font Vivanco and Voet, 2014 show modelling approaches for different types of rebound effects that mainly combine economic modelling and LCA. However, as Suski et al., 2021 point out, by addressing mainly price effects, only a limited number of types of rebound effects can be included. This is why scientists also suggest combining LCA with methods from social sciences to better capture and model changes in usage patterns, such as social practice theory (Suski et al., 2021), actor-network theory (Niero et al., 2021) or behavioural science research (Polizzi di Sorrentino et al., 2016). Suski et al., 2021 stress the relevance of an appropriate functional unit definition for the inclusion of higher-order effects and, to avoid system expansion, propose household level as reference instead of the product or service to be assessed.

In the supplementary publication Pohl et al., 2019b, based on previous work from Miller and Keoleian, 2015 and Shahmohammadi et al., 2017, three groups of parameters related to user behaviour and decisions are defined that may influence environmental assessments of products and services (see Figure 2): technology-related parameters (e.g. sourcing of raw materials, energy efficiency), product-related parameters (e.g. choice of products and services), and behaviour-related parameters (e.g. rebound effects, active service life).

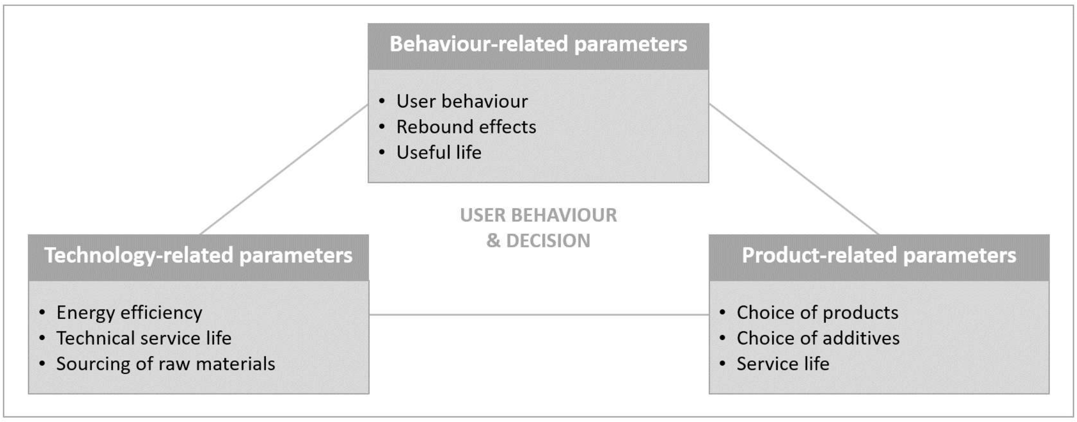

Figure 2: User behaviour affecting the environmental performance of products, based on Miller and Keoleian, 2015; Pohl et al., 2019b; Shahmohammadi et al., 2017.

In addition to methodological issues of integrating user behaviour in LCA, data availability also plays a major role. Daae and Boks, 2015; Pohl et al., 2019b; and Polizzi di Sorrentino et al., 2016 propose suitable supplementary methods for the collection of primary data for a more realistic modelling of user behaviour in LCA. Bieser et al., 2022 show how time use data and energy consumption data can be combined.

1.1.3 Smart homes as an example for ICT-based services in the residential sector

One area in which ICT-based services may reduce environmental impact is the home. The term *smart home* is used to describe networked devices, sensors and appliances in the home whose purpose is to provide residents with a variety of new or improved services such as energy management, comfort, control or security (Balta-Ozkan et al., 2014). Various different definitions of the term *smart home* can be found in the literature, both with regard to technical and operational factors and functionalities provided (e.g. Aldrich, 2003; Balta-Ozkan et al., 2014; Strengers and Nicholls, 2017; Wilson et al., 2015). In this thesis, the definition provided by Gram-Hanssen and Darby, 2018 is adopted, which understands smart homes as those ”in which a communications network links sensors, appliances, controls and other devices to allow for remote monitoring and control by occupants and others”. In the following, the term smart home system (SHS) is used to describe the devices and ICT infrastructure that form the smart home.

In the SHS, energy-consuming processes can be monitored and controlled through the use of sensors and (learning) algorithms (Habibi, 2017). Hence, for SHS, the environmental reduction potential refers in particular to savings in energy and related GHG emissions. Applications include home energy management systems, smart thermostats, smart plugs and lighting control (IEA 4E, 2018).Thus, SHS are considered a great opportunity to lower overall household energy demand (Balta-Ozkan et al., 2014). In contrast, other ICT-based services in the smart home, such as comfort, security or assisted living, are not primarily associated with energy saving potentials. If these services are also used, the environmental benefit of energy management could therefore be neutralised or even overcompensated by higher energy consumption (Hargreaves et al., 2018). However, it is quite possible for an SHS component to offer several services simultaneously (Balta-Ozkan et al., 2014). For example, smart heating control serves both energy management (by adapting and optimising the heating process to the surrounding environment) and comfort (by automating processes).

Applying the framework of the environmental effects of ICT (see Figure 1), the environmental effects of an SHS can be described as follows: The direct effects of an SHS describe all environmental expenditures along the system's life cycle, from production to use and disposal of the SHS devices. Optimisation effects describe the amount of energy saved by the energy management function. Rebound effects describe changes in user behaviour towards more energy-intensive behaviour in response to expected efficiency gains. For example, higher heating temperatures can be set or more rooms can be heated. Induction effects describe the environmental effects caused by the use of additional SHS services such as security or comfort.

The question of whether and how SHS may reduce environmental consumption has been discussed by various research disciplines. With the aim to increase the efficiency of energy-consuming processes, research on the technical development of SHS focuses on topics such as system integration and standardisation (Risteska Stojkoska and Trivodaliev, 2017; Toschi et al., 2017), or energy demand management and prediction (Albuquerque et al., 2018; Arghira et al., 2012; Lee and Choi, 2020; Lu et al., 2017). The technical energy saving potential of different smart home technologies is, for example, indicated as 5-10% of heating energy for smart thermostats, 11-20% of heating or cooling energy for smart windows control, or 20% of overall energy use for home energy management systems (IEA 4E, 2018). However, as Brom et al., 2018; Ford et al., 2017; and Gram-Hanssen, 2013 have shown, it is in particular the interaction between the user and the SHS that determines the extent to which the theoretical savings potentials of SHS can be realised.

With regard to how the SHS is actually used, research involves questions about who the users are (Wilson et al., 2015, 2017), what motives and intentions are associated with SHS use (Ahn et al., 2016; Nilsson et al., 2018) or how users adopt to the new technology in their home (Balta-Ozkan et al., 2013; Hargreaves et al., 2018). Wilson et al., 2017 find that smart home users can be characterised as *early adopters* who, for example, have a higher incomes than mass market users. Nilsson et al., 2018 compare the overall electricity demand of a group of *early adopter* households with home energy management systems and find that the impact on electricity demand is very individual and can lead to changes of about +/-40% in electricity demand. Factors influencing energy behaviour are related to values and attitudes, knowledge about own energy consumption or perception of control (Nilsson et al., 2018). Ahn et al., 2016 find that the intention to use an SHS can be predicted by constructs related to technology enthusiasm and consumerism rather than environmental concern. This is also shown in a study of existing narratives and desires of industry and users by Rohde and Santarius, n.d., who find that energy-saving functions play a little role. Instead, visions relate to more comfortable lifestyles by offering additional services such as pre-heating of rooms, integration of entertainment systems or better control over devices (Rohde and Santarius, n.d.).

In investigating the way SHS are used, Hargreaves et al., 2018 find that not all functions offered by SHS are always used, which could minimise their energy saving potential. Nicholls et al., 2020 point out that SHS devices are not only used to reduce energy demand, but also for expanded use for reasons such as security or entertainment, which could lead to an overall increase in energy consumption. Tirado Herrero et al., 2018 argue that the introduction of SHS may therefore result in the enhancement of unsustainable lifestyles instead of helping to reduce household energy consumption. Consequently, aspects related to who the user is, which parts of the SHS are used and how the SHS is actually used should be taken into account when determining the overall environmental impact of SHS.

However, when reviewing research on the environmental assessment of SHS, effects involving variances in user behaviour are rarely considered. Research on SHS from a life cycle perspective is primarily concerned with the energy saving potential of single SHS components. Some studies further determine the associated payback time, which describes the point in time at which environmental effects from production and operation have been amortised within a particular savings scenario. However, types of environmental effects of SHS considered in the individual studies are very different, which make comparison difficult. According to Beucker et al., 2016, the direct effects from the production and operation of the energy management system reduce the technical optimisation potential for energy demand and GHG emissions only slightly. In contrast, for different types of home energy management systems, Dam et al., 2013 and Louis and Pongrácz, 2017 conclude that, depending on the type of system, direct effects from production and operation reduce the technical optimisation potential, sometimes considerably.

Other studies do not consider environmental effects from manufacturing at all and only compare the operational energy demand and savings potential of SHS during the use phase. For example, for smart heating control, Kersken et al., 2018 estimate comparatively high average savings potentials of up to 19% of heating energy, while Rehm et al., 2018 find average heating energy savings of only 4%. One possible reason for the significant differences in the savings potentials through smart heating control in both studies are the different environmental effects of SHS that were taken into account. While Kersken et al. use building simulation software to determine the technically possible savings potential (i.e. optimisation effect), Rehm et al. use measured data from a field study with more than 120 households and thus also include changes in usage behaviour (i.e. rebound effects) in the calculation. That rebound effects indeed could alter the net saving potential of an SHS is further shown in a study by Walzberg et al., 2020 on the reduction potential of smart electricity management and information feedback. In summary, the informative value of these studies is limited, as direct effects from the production of the SHS and/or higher-order effects related to user behaviour are not always included in the assessment.

1.2 Gaps and challenges

From the state of research presented in Section 1.1, it follows that the environmental saving potential of ICT-based services cannot yet be precisely determined. This can be traced back to both data availability challenges and methodological challenges related to the inclusion of use-related higher-order effects in environmental assessments. As the omission may lead to an overestimation of the importance of ICT-based services in reducing energy, GHG emissions or resources, this can lead to a lack of validity of certain results. The following research gaps and challenges can be identified and will be addressed in this thesis:

- There is a need for a stronger integration of use-related higher-order effects of ICT into environmental assessments, as called for by several authors (Arvesen et al., 2011; Börjesson Rivera et al., 2014; Horner et al., 2016).

- There is a lack of both suitable approaches and empirical data to accurately determine the environmental saving potential of ICT-based services. One approach to capture and integrate use-related higher-order effects into LCA in a scientifically sound way could be to combine LCA with other methods (Polizzi di Sorrentino et al., 2016).

- Independently from ICT, there are a number of ideas and suggestions on how to integrate use-related effects into LCA (see for example Niero et al., 2021; Suski et al., 2021), or how to address variance of results due to different usage patterns in uncertainty analyses (Ross and Cheah, 2017), but their operationalisation and application in case studies is lacking.

- For the case of smart homes, studies assessing the environmental saving potential have been criticised for their limited scope, e.g. because only the operational phase is taken into account, or only intended higher-order effects are included (Dam et al., 2013). In order to increase the informative value of these studies, a holistic environmental assessment that covers effects along products' life cycles as well as their application and use is needed.

There are further research gaps that are not addressed in this thesis:

- Often simplified LCA models of ICT-based services are applied due to the lack of available inventory data for both ICT devices and ICT infrastructure (Moberg et al., 2014). Due to the high degree of intransparency in the production process and the very rapid change of suppliers, it is not to be expected that the data availability will improve (Capelleveen et al., 2018). One approach could be the development of generic product models for different ICT product types (e.g. smartphone, tablet, router, sensor) which would drastically reduce the need for inventory data. In this case, however, it would also be a challenge to keep the data up to date.
- When using ICT-based services, other types of rebound effects may also occur, such as time rebound, space rebound or motivational rebounds (Börjesson Rivera et al., 2014). Empirical studies are lacking here so far.
- Increasing deployment of ICT brings with it both dynamic and infrastructural implications (Mulrow et al., 2022). Building on attributional assessments, these could be investigated using macroeconomic scale-up or agent-based modelling.
- More case studies on environmental effects of ICT-based services in areas such as agriculture, industry or new forms of consumption are needed in order to better understand challenges and potentials that come with the ongoing introduction of ICT-based services.

1.3 Aim and structure of the thesis

The aim of this thesis is to develop an approach to how higher-order effects can be integrated into LCA of ICT, and thus to contribute to a sound analysis of the environmental potential of ICT at the application level. This thesis comprises of five chapters. Chapter 1 begins with an introduction to the topic of the environmental effects of ICT, and its assessment with LCA, and presents the case of smart homes as an example for ICT-based services in the residential sector. Further, on the basis of the presented state of research, research gaps and challenges are identified and the aim and structure of the thesis are presented. In Chapter 2, the underlying research approach of this thesis is presented and research questions and research tasks are developed. In addition, given the cumulative character of the thesis, linkages of core and supplementary publications and research questions are shown. The three core publications, summaries of results and updates of results, where necessary, are then presented in Chapter 3. In Chapter 4, the main findings of this research as well as the modelling approach and transferability are discussed, and future research is derived based on the analysis. Concluding remarks are presented in Chapter 5.

2 Research approach

In this chapter, based on a transdisciplinary setting (Section 2.1), the development of research questions and related research targets is presented (Section 2.2) and linkages between publications, research questions and research targets are shown (Section 2.3).

2.1 Transdisciplinary setting

The dissertation was developed as part of the inter- and transdisciplinary junior research group "Digitalization and sustainability", which conducts research on the societal and environmental impacts of the provision and use of ICT. Transdisciplinary research aims at addressing societally relevant problems by integrating knowledge from scientists as well non-academic stakeholders such as business, government or civil society. Collaborative knowledge production involves joint development of research questions, as well as the integration of research methods from different disciplines and the dissemination of research results to different societal actors (Lang et al., 2012).

In this sense, following a transdisciplinary research approach, interdisciplinary collaboration with researchers from the junior research group as well as findings from transdisciplinary workshops with societal actors contributed to the development and analysis of the research questions of this thesis. Interdisciplinary collaboration with social scientists and macro-economists with regard to the multiple environmental effects of ICT-based services at the micro and macro level (e.g. Frick and Matthies, 2020; Kopp and Lange, 2019; Santarius and Soland, 2018) informed research question RQ1. Interdisciplinary collaboration with social scientists (Frick and Nguyen, 2021; Rohde and Santarius, n.d.) as well as transdisciplinary cooperation with societal actors supported research questions RQ2 + RQ3.

2.2 Development of research questions

The overall goal of this thesis is to investigate how to integrate higher-order environmental effects into LCA of ICT. This will be pursued through the development and operationalisation of a conceptual framework for assessing the environmental effects of ICT-based services, with a focus on higher-order effects. In the following, three research questions and related research tasks are presented. Taking an incremental approach, the direction of research questions RQ2 + RQ3 was developed based on the main challenges identified in RQ1. RQ3 further draws on findings from RQ2 (see Figure 3).

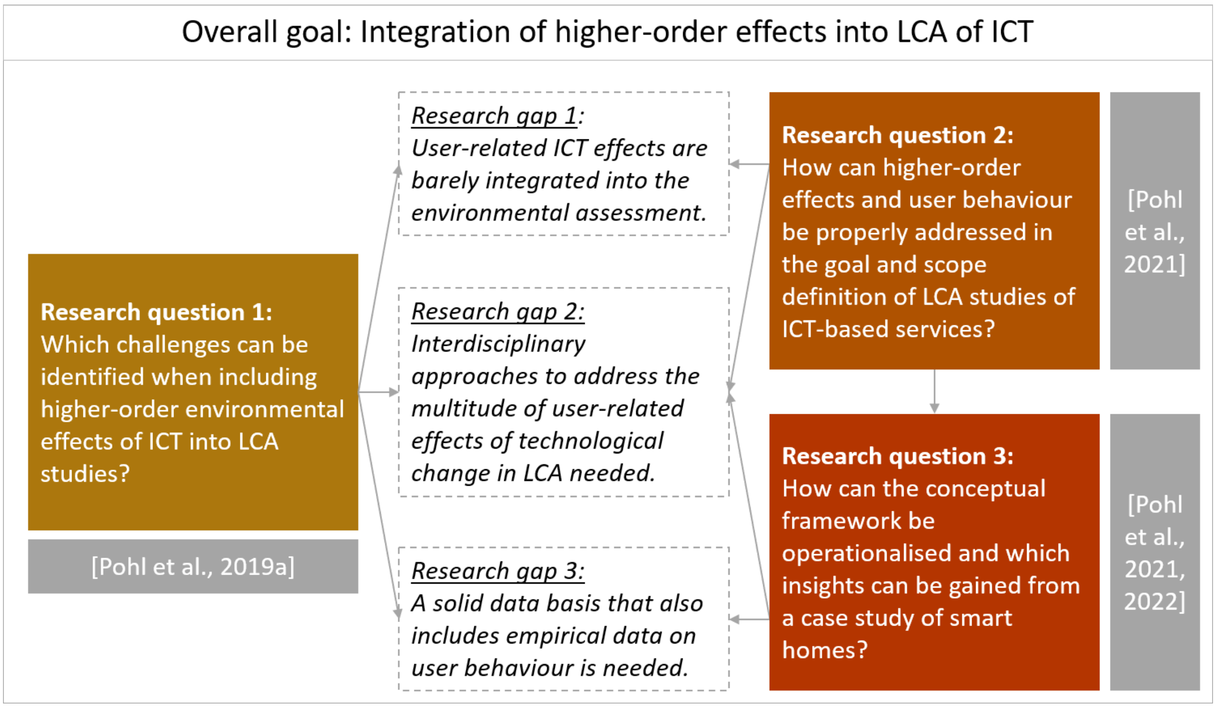

Figure 3: Development of research questions

On a theoretical level, the conceptualisation of the environmental effects of ICT has been underway for more than two decades (Hilty and Aebischer, 2015; Mickoleit, 2010; Sui and Rejeski, 2002). Recently, the role of indirect or higher-order effects of ICT has become a focus of attention. This is because the higher-order effects of ICT are highly significant for the overall environmental impact of ICT (Bieser and Hilty, 2018; Horner et al., 2016; Kaack et al., 2022). At the application level, both effects resulting from the technical saving potential of the ICT-based services (through optimisation or substitution), and effects resulting from changes in user behaviour (i.e. rebound and induction effects) can be summarised under higher-order effects. In addition to these, there are other higher-order effects at the systemic (macroeconomic) level (e.g. macroeconomic rebound effects or sectoral change). This thesis focuses on LCA studies that focus on ICT-based services. Approaches focusing only on the direct effects of ICT, i.e. the environmental effects along the life cycle of ICT hardware or on the macroeconomic level, are outside the scope of this thesis.

Empirical results on the environmental impact of ICT-based services are rather heterogeneous. On the one hand, studies examine very different use cases, which are also mixed in their results regarding the environmental saving potential of energy, resources or GHG emissions. On the other hand, applied methodological approaches are very diverse, e.g. in terms of system boundaries and the definition of the product system, but also in terms of the inclusion of various higher-order effects in the modelling. This makes it not only difficult to compare results, but also calls into question the overall validity of particular results, as this omission may lead to the importance of ICT-based services in reducing energy, GHG emissions or resources being overestimated. In this context, methodological issues are often cited as one of the reasons for not including higher-order effects in the modelling. The first research question RQ1 addresses this gap:

RQ1: Which challenges can be identified when including higher-order environmental effects of ICT into LCA studies?

This research question encompasses both an applicable framework of environmental effects of ICT, and current approaches addressing higher-order effects of ICT in LCA studies and resulting research needs. Accordingly, three research tasks RT 1.1-1.3 were derived:

- RT1.1: Revision and harmonisation of existing frameworks on the environmental effects of ICT
- RT1.2: Review of current approaches in LCA, and how these approaches take into account the higher-order effects of ICT
- RT1.3: Gap analysis and derivation of research needs

As shown in Section 1.1, the higher-order effects of ICT can contribute to both increasing and decreasing resource use. While the intended, mostly environmentally beneficial effects result from the technical saving potential of the ICT-based services (through optimisation or substitution), environmentally harmful effects often stem from changes in user behaviour (i.e. rebound and induction effects). When it comes to the integration of higher-order effects of ICT into LCA, one challenge is that resulting behavioural changes from the application of ICT have not yet been sufficiently integrated into LCA studies (see “Challenges” in Figure 3). This is partly due to a lack of an underlying conceptual framework for integrating higher-order effects into LCA that also includes behavioural aspects. The second research question RQ2 reflects the gap:

RQ2: How can higher-order effects and user behaviour be properly addressed in the goal and scope definition of LCA studies of ICT-based services?

This research question aims at proposing a conceptual framework that captures the various higher-order effects of ICT and makes them transferable to LCA. Accordingly, two research tasks RT 2.1-2.2 are derived.

- RT2.1: Transfer of use-related higher-order effects of ICT into the life cycle perspective and subsequent classification of the parameters
- RT2.2: Development of a conceptual framework for the integration of the user-driven parameters from RT2.1 into LCA modelling

The conceptual framework *The user perspective in LCA*, as developed under RQ2, provides an approach to how the higher-order effects of ICT can be captured and integrated more stringently into LCA studies. However, before the user-driven parameters can be integrated into a specific LCA study, they first need to be operationalised, i.e. the parameters need to be translated into (measurable) indicators of a particular case. Depending on the context, it may be useful to adopt an interdisciplinary approach, e.g. with behavioural sciences, to ensure that the user-driven parameters are integrated into the LCA study in a scientifically sound way. It follows from the conceptual framework that the inclusion of use-related higher-order effects of ICT into LCA studies is reflected in particular in the goal and scope definition. In addition, the interdisciplinary approach may also include the collection of further primary behavioural data as part of the inventory collection or the interpretation of the results (Polizzi di Sorrentino et al., 2016).

The relevance of interdisciplinary approaches for the sound integration of higher-order effects of ICT into LCA studies was also highlighted as another challenge identified under RQ1 (see “Challenges” in Figure 3). There is a lack of interdisciplinary approaches, and of (behavioural) data to take into account the multitude of user-related effects of technological change in the LCA. Accordingly, the third research question RQ3 focuses on the application of the conceptual framework in LCA in a case study:

RQ3: How can the conceptual framework be operationalised and which insights can be gained from a case study of smart homes?

This research question aims at presenting an interdisciplinary approach to how the conceptual framework *The user perspective in LCA* can be operationalised and implemented. Based on a case study, RQ3 further aims to draw conclusions both about the overall results of the environmental assessment of ICT, and the methodological applicability, if higher-order effects are also included. Accordingly, three research tasks RT 3.1-3.3 are derived.

- RT3.1: Operationalisation of conceptual framework and performance of a case study test
- RT3.2: Proof of concept and generation of case study results
- RT3.3: Derivation of conclusions for LCA research and ICT assessment

2.3 Linkage of publications, research questions and research targets

The three core publications of this thesis, supplemented by three additional publications, contribute to answer the research questions and related research targets as outlined in

Section 2.2. Table 1 gives an overview of the approaches and methods of the core publications and supporting publications. Linkage between all publications, research questions and research tasks are depicted in Table 2.

Table 1: Overview of approaches and methods of core publications and supporting publications. Core publications are highlighted in **bold**.

Publication	Scientific contribution	Approach	Method
Pohl et al, 2019a: How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches. Journal of Cleaner Production 219.	Analysis of modelling approaches in LCA of ICT that include higher-order effects	Conceptual	Systemic literature review
Pohl et al, 2019b: Beyond Production - the Relevance of User Decision and Behaviour in LCA. Springer.	Discussion of LCA modelling aspects with regard to addressing user behaviour in LCA	Conceptual	
Vaddadi et al, 2020: Towards a conceptual framework of direct and indirect environmental effects of co-working. ACM.	Analysis of environmental effects of co-working	Conceptual and empirical	Time diaries, energy footprint
Suski et al, 2020: All you can stream: Investigating the role of user behavior for greenhouse gas intensity of video streaming. ACM.	Analysis of environmental effects of video streaming	Empirical	Online survey, carbon footprint
Pohl et al., 2021: Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home? Journal of Cleaner Production 312.	Development of a conceptual framework addressing user behaviour in LCA, analysis of environmental effects of the average SHS in Germany	Conceptual and empirical	Online survey, LCA
Pohl et al., 2022: Assessing the environmental performance of ICT-based services: Does user behaviour make all the difference? Sustainable Production and Consumption 31.	Analysis of environmental effects of SHS in Germany with a focus on user-driven parameters, socioeconomic characteristics of the users and user motivation	Empirical	Online survey, LCA, regression analysis

The **first core publication** is a review of different approaches in LCA towards how to account for the higher-order effects of ICT and addresses RQ1:

Pohl, J., Hilty, L.M., Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher-order effects of ICT application: A review of different approaches. Journal of Cleaner Production 219, 698–712. https://doi.org/10.1016/j.jclepro.2019.02.018

Following RT 1.1, this publication first presents a revision of the framework of the environmental effects of ICT by Hilty and Aebischer, 2015. Then, results of a systemic review of the scientific literature published between 2005 and 2018, focusing on LCA studies on the environmental effects of ICT-based services, is presented. It is investigated whether and how these studies take higher-order effects of ICT application into account. (RT 1.2). The publication concludes by proposing a future research agenda (RT 1.3).

In the **second core publication**, a conceptual framework for integrating user-driven parameters into LCA is presented and applied in a first case study on the environmental effects of the average SHS in Germany. This publication thus addresses both RQ2 and RQ3:

Pohl, J., Frick, V., Höfner, A., Santarius, T., Finkbeiner, M., 2021. Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home? Journal of Cleaner Production 312, 127845. https://doi.org/10.1016/j.jclepro.2021.127845

RT 2.1-2.2 are addressed in Section 1-3 of this publication. First, a conceptual framework for integrating user-driven parameters into LCA is developed. Based on initial considerations from Pohl et al., 2019b, higher-order effects from the application of ICT are transferred into the life cycle perspective by assigning them corresponding user-driven parameters (RT 2.1). In a second step, corresponding LCA modelling characteristics are assigned to these parameters (RT 2.2).

The Sections 4-6 of this publication address RT 3.1-3.2. The conceptual framework is operationalised using an interdisciplinary study design and applied in a case study of an average SHS with smart heating in Germany (RT 3.1). The LCA analyses the net savings effects of the average smart homes for various impact categories when higher-order effects of ICT are also included into the environmental assessment (RT 3.2).

The **third core publication** analyses the environmental effects of SHS in Germany with a focus on user-driven parameters, socioeconomic characteristics of the users and user motivation. It addresses RQ3:

Pohl, J., Frick, V., Finkbeiner, M., Santarius, T., 2022. Assessing the environmental performance of ICT-based services: Does user behaviour make all the difference? Sustainable Production and Consumption 31, 828–838. https://doi.org/10.1016/j.spc.2022.04.003

Following RT 3.1, this publication combines life cycle modelling and behavioural science in an interdisciplinary study design, applying the conceptual framework from the second core publication to the smart homes case in Germany. Using the same sample as in the previous publication, the role of various use-specific effects (i.e. the use-related higher-order effects of ICT), such as induction effects and rebound effects is investigated for the environmental assessment of SHS (RT 3.2). Based on the results, following RT 3.3, implications for research and practice are derived.

Table 2: Linkage of core publications, supporting publications and research questions. Core publications are highlighted in **bold**.

Research question	Research tasks	Publication	
Which challenges can be identified when including higher-order environmental effects of ICT into LCA studies?	Task 1.1: Revision and harmonisation of existing frameworks on the environmental effects of ICT Task 1.2: Review of current approaches in LCA, and how these approaches take into account the higher-order effects of ICT Task 1.3: Gap analysis and derivation of research needs	**Pohl et al., 2019a**	
How can higher-order effects and user behaviour be properly addressed in the goal and scope definition of LCA studies of ICT-based services?	Task 2.1: Transfer of use-related higher-order effects of ICT into the life cycle perspective and subsequent classification of the parameters Task 2.2: Development of a conceptual framework for the integration of the user-driven parameters from RT2.1 into LCA modelling	Pohl et al., 2019b Vaddadi et al., 2020	**Pohl et al., 2021**
How can the conceptual framework be operationalised and which insights can be gained from a case study of smart homes?	Task 3.1: Operationalisation of conceptual framework and performance of a case study test Task 3.2: Proof of concept and generation of case study results Task 3.3: Derivation of conclusions for LCA research and ICT assessment	Vaddadi et al., 2020 Suski et al., 2020	**Pohl et al., 2021** **Pohl et al., 2022**

Beside the core publications of this thesis, there are three **supporting publications** co-authored by the author of this thesis contributing to the research tasks RT 2.1, RT 3.1, and RT 3.2.

In the book chapter *Beyond Production—the Relevance of User Decision and Behaviour in LCA* (Pohl et al., 2019b), initial considerations are made on the relevance of user behaviour in LCA. The classification of use-relevant parameters in LCA presented in the chapter is later taken up and specified in the conceptual framework *The user perspective in LCA* in Publication 2, thus contributing to RT 2.1. The chapter is based on a workshop organised by the authors at *Ökobilanzwerkstatt 2018* in Osnabrück.

In the conference paper *Towards a conceptual framework of direct and indirect environ-*

mental effects of co-working (Vaddadi et al., 2020), the framework of the environmental effects of ICT, as presented in Publication 1, is adapted to investigate the environmental effects of co-working. Based on the framework, the direct effects and higher-order effects of co-working are identified and related energy impacts are calculated using behavioural data from a Living Lab study in Stockholm, Sweden. The study thus contributes to RT 2.1, RT 3.1. and RT 3.2. The conference paper was presented at *ICT4S 2020*.

In the conference paper *All you can stream: Investigating the role of user behaviour for greenhouse gas intensity of video streaming* (Suski et al., 2020), an interdisciplinary approach is applied to investigate the effect of use-specific determinants on greenhouse gas intensity when streaming videos. An online survey is used to collect usage-specific data, which is then incorporated into an LCA. Considerations on the interplay of behavioural science and life cycle modelling for the investigation of higher-order environmental effects of ICT are tested using the example of video streaming, thus contributing to RT 3.1 and RT 3.2. The conference paper was presented at *ICT4S 2020*.

3 Results

In this chapter, the results of the thesis are presented in three subsections. In each subsection, bibliographic information, CRediT author statement and a summary of the results are compiled.

3.1 Higher-order effects of ICT – current assessment approaches and resulting research needs

This section analyses current environmental assessment approaches integrating higher-order effects of ICT in LCA studies and identifies future research needs. This section contains the following publication:

Pohl, J., Hilty, L.M., Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher-order effects of ICT application: A review of different approaches. Journal of Cleaner Production 219, 698–712. https://doi.org/10.1016/j.jclepro.2019.02.018

CRediT author statement:

- Johanna Pohl: Conceptualisation, Methodology, Data curation, Investigation, Formal analysis, Writing - original draft, Writing - review & editing;
- Lorenz Hilty: Writing - review & editing, Supervision;
- Matthias Finkbeiner: Writing - review & editing, Supervision.

Results summary:

In the revision of the framework of the environmental effects of ICT, the taxonomy of environmental effects were organised in a matrix with different levels (first-order vs. higher-order effects) and perspectives (technology vs. user vs. systemic perspective). The environmental effects that are mostly considered in LCA studies are mainly at the application level. According to the taxonomy, these are first-order effects and higher-order effects from a technology and user perspective.

Overall, 25 LCA studies on first-order and higher-order environmental effects of ICT-based services were identified by means of a systemic literature research. The majority of studies investigated environmental effects through e-materialisation. Significantly fewer studies examined cases related to telework, e-commerce and monitoring & control. This is also reflected in the higher-order effects examined: Only studies on monitoring & control services investigated optimisation effects. All other studies examined substitution effects due to the application of ICT. Other, presumably unintended higher-order effects such as induction effects and rebound effects were additionally included in the study scope, though only in some studies. It was found that depending on the type of higher-order effect, integration into LCA modelling differed. A comparative study design was selected for the integration of intended higher-order effects from a technology perspective (optimisation, substitution). Unintended higher-order effects from a user perspective, if included at all, were addressed by means of sensitivity analysis, scenario modelling, allocation or customised modelling.

To better understand the potential of ICT applications for the reduction of environmental impact, the following research needs are identified: need for case studies on ICT-based services in rarely addressed areas such as housing, production or practices such as sharing/renting; need for interdisciplinary approaches to address the multitude of user-related effects such as induction effects and rebound effects in LCA; need for combined approaches to include dynamic and infrastructural effects into LCA.

Results update:

In order to provide up-to-date results, the systemic literature research was extended to the years 2019 to 2021.

Seven additional studies were identified in the fields of e-commerce (Amatuni et al., 2020), and monitoring & control (Bacenetti et al., 2020; Chazarra-Zapata et al., 2020; Gawron et al., 2019; Ipsen et al., 2019; Yang et al., 2019; Zhang et al., 2019). The analysed intended higher-order effects were substitution, and optimisation. These were integrated in the modelling through a comparative study design. In addition, rebound effects were included in the analysis in the study by Amatuni et al., 2020. These were integrated directly into the different scenarios based on user data.

Thus, with regard to the initial research questions from Publication 1, no further approaches related to the integration of higher-order effects of ICT in LCA could be identified.

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Review

How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches

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A B S T R A C T

Information and communication technology (ICT) is often considered a technology for reducing environmental emissions by increasing energy and resource efficiencies of processes. However, due to other effects of ICT, such as rebound and induction effects, the net benefits of ICT in terms of environmental impact are by no means assured. Even though the relevance of indirect or higher order effects has become a well-known issue in recent years, their environmental assessment remains controversial. Life cycle assessment (LCA) is one of the most established environmental assessment methods for modelling the environmental effects of goods and services throughout their life cycle. Although LCA is traditionally rather product-focused, there exist also LCA-based approaches to assess higher order effects of technology replacement and optimization.

This paper examines whether and how LCA case studies on environmental effects of ICT already take into account related higher order effects. A systematic review of scientific literature published since 2005 has been conducted and 25 case studies were analyzed in detail. The following research questions were addressed: i) Which products are assessed? ii) Which higher order effects of ICT are considered; and iii) how is the integration of higher order effects methodically realized? The results show that few case studies were concerned with the environmental effects of the introduction of ICT services in commerce, telework and monitoring and control. Most studies investigated the substitution of certain media with electronic devices or digital services. It was found that technology-based higher order effects, such as optimization and substitution, are usually included in the assessment by choosing comparative study designs, while user-related higher order effects, such as rebound effects and induction effects, are less often considered. For the latter effects, methodological integration was mainly provided by scenario modelling and sensitivity analysis. Overall, most studies chose an attributional LCA approach. It can be concluded from the results that, in particular, user-related effects such as rebound effects have not yet been frequently included in the environmental assessment of ICT. The identified research gaps include in particular interdisciplinary approaches on how changing use patterns can be more strongly observed in LCA.

Contents

Abbreviations: ALCA/ CLCA/ IO-LCA, attributional/consequential/input-output life cycle assessment; GHG, greenhouse gases; CLEER, Cloud Energy and Emission Research; EVR, eco costs/value ratio; ICT, Information and communication technology; ILCD, International Reference Life Cycle Data System; MEErP, Methodology for ecodesign of energy-related products; MIPS, Material input per unit of service; RMD, raw material depletion; RQ, research question; SLR, systematic literature research.

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1. Introduction

ICT's environmental effects have been under discussion for more than a decade (see Andrae and Edler, 2015; Arvesen et al., 2011; Berkhout and Hertin, 2004; Hilty and Aebischer, 2015; Horner et al., 2016; Malmodin et al., 2014; Murugesan, 2008). The understanding of potential effects developed from “unrealistic technology optimism” (Arvesen et al., 2011) towards a comprehensive understanding of positive and negative environmental effects (Börjesson Rivera et al., 2014). Over the years, a taxonomy of first order and higher order environmental effects has emerged (Horner et al., 2016). While first order effects can be traced back to the material and energy demand along the product life cycle of ICT hardware, higher order effects result from the application and use of ICT. ‘Higher order effect’ is an umbrella term for all positive or negative impacts that result from the services that ICT devices provide to their users. Due to the fact that ICT induces a broad spectrum of behavioral and structural changes, the final (indirect) effect on the environment, in particular how the energy and resource efficiencies of processes are affected, is not a priori clear. The relevance and ambivalence of higher order effects has become obvious in studies focusing on specific fields of ICT application. For example, Williams and Tagami (2002) compared e-commerce and conventional retailing in a study of the Japanese book sector. Results showed that e-commerce in urban areas requires significantly more energy per book, while in rural areas both systems use a similar amount of energy. These mixed results are confirmed by other studies on e-commerce (Edwards et al., 2010; Mangiaracina et al., 2015; van Loon et al., 2015), by studies on movie delivery (Seetharam et al., 2010; Shehabi et al., 2014), and by studies on mobility alternatives to business meetings (Borggren et al., 2013).

The integration of higher order effects, such as rebound effects, into the environmental assessment can be decisive for the overall results (Arvesen et al., 2011; Hakansson and Finnveden, 2015; Røpke, 2012; Røpke and Christensen, 2013). However, the methodological integration of these effects into the assessment remains challenging (Börjesson Rivera et al., 2014; Finkbeiner et al., 2014; Heijungs et al., 2009; Hertwich, 2005; Miller and Keoleian, 2015; Zamagni et al., 2008). This has also been shown in earlier literature reviews on the environmental impact of ICT, for example in a study by Arushanyan et al. (2014), who generally examined the state of the art in life cycle assessment (LCA) studies of digital products and services. Horner et al. (2016) examined literature on higher order effects of ICT. Based on these findings, Bieser and Hilty (2018) identified a variety of methods for assessing higher order ICT effects, including LCA. However, to the authors' knowledge, a specific review of LCA approaches to assessing higher order effects of ICT is still lacking. This paper thus examines whether and how LCA case studies on environmental effects of ICT take into account related effects of higher order. The review is not intended to compare the assessment results of these studies, but provides a methodological overview.

The survey consists of case studies assessing the environmental higher order effects of ICT applications that were published in scientific journals between 2005 and 2018. The following research questions (RQ) are tackled by reviewing these LCA studies on ICT applications:

RQ (1) Which products are assessed?
RQ (2) Which higher order effects are considered?
RQ (3) How is the integration of higher order effects methodically realized?
- Which specific approaches are applied to integrate higher order effects?
- Which types of impacts are considered?
- Which specific LCA methods are applied?

The remainder of the paper is structured as follows: In Section 2, the theoretical model of environmental effects of ICT is introduced, followed by a summary of environmental assessment methods of technological change. The methods section (Section 3) explains how the literature was selected and evaluated for the review. Details of the literature review are then presented in the results section (Section 4), followed by the discussion of relevant findings in Section 5. The paper ends by outlining future research needs in the concluding Section 6.

2. Background and theoretical model

ICT is often described as a transformative technology with the potential to fundamentally change society, including the prevailing lifestyles and patterns of production and consumption. The application of ICT therefore has a large number of positive and negative environmental effects. In the following, the underlying taxonomy of environmental effects of ICT is introduced, followed by a summary of environmental assessment methods of technological change.

2.1. A framework of environmental effects of ICT

Berkhout and Hertin (2004) introduced a taxonomy of environmental effects which has been used and revised several times (Hilty and Lohmann, 2013). Usually, a division into two or three levels of effects is assumed: First order effects (direct effects) trace back to the material and energy demand along ICT's product life cycle (Schien et al., 2013). Higher order effects (indirect effects) refer to the application of ICT and the resulting behavioral and structural effects (Røpke, 2012). In other words, first order effects describe the effort required to provide an ICT-based service. The term higher order effects summarizes both the intended functions/benefits and unintended effects of an ICT-based service or ICT application. While some authors refrain from further classification (Börjesson Rivera et al., 2014), others divide higher order effects into further levels, such as into indirect and systemic effects (Berkhout and Hertin, 2004), second order/enabling and third order/systemic effects (Hilty and Aebischer, 2015) or application/service-oriented effects and systemic effects (Horner et al., 2016). However, the assignation of particular effects to certain levels is not always congruent and complete (Horner et al., 2016), especially with effects resulting from interactions between technology systems and changes in user behavior. For example, both Berkhout and Hertin (2004) and Hilty and Aebischer (2015) assign user-related effects, such as rebound effects, to the systemic level. However, rebound effects occur not only at a systemic level, but also at the level of individual application. This has already been reflected in a further development of the framework by Horner et al. (2016), but besides rebound effects, further behavior-related effects are missing. This article builds on this aforementioned work and adds further behavior-related effects (see Fig. 1). To avoid confusion with regard to the term “indirect effects”, which is used with different meanings even in closely related contexts, the term “higher order effects” is used instead. This covers both the application and system levels.

Among the intended higher order effects of ICT which enable increasing resource efficiency of processes, are optimization and substitution effects. Optimization effects occur in those processes in which information about a system is used to improve a process (Bonvoisin et al., 2014). In this case, ICT devices such as sensors are used to generate data, and other ICT devices to derive useful information from them. Substitution effects of ICT occur where other types of products are replaced by their digital equivalents (Börjesson Rivera et al., 2014). Both effects are aimed at dematerialization (sometimes, more specifically, decarbonization) and are mostly induced effects, where an existing technology is modified or replaced with less material- or energy-intensive technologies or process patterns. Nevertheless, the substitution effect can also contribute to rematerialization. This can be the case if the direct effects of the substitute exceed substitution effects, or if the substitution is only partial (Berkhout and Hertin, 2004). To a certain extent, this also applies to optimization processes, when direct effects of additional ICT devices exceed the net optimization effects.

Efficiency improvements due to optimization can also be partially compensated or even over-compensated for by changes in use patterns. In the literature, such compensating effects are referred to as rebound effects or induction effects (Gossart, 2015; Greening et al., 2000). Rebound effects are often divided into direct rebound effects and indirect rebound effects and lead to an increased demand of the same or other products (Sorrell, 2007). In recent years, the understanding of the rebound concept as such has expanded beyond an economic analysis (van den Bergh, 2011). Galvin (2015) notes, that the usual division into direct and indirect rebound effects does not fit well with ICT applications, as the usual “satiation of consumer need does not seem to occur [...] [and] seems constantly to beget new human needs”. For ICT applications, Börjesson Rivera et al. (2014) identify various types of rebound effects that can be analyzed on an application level. These are (1) direct economic rebounds, (2) indirect economic rebounds, (3) time rebounds and (4) space rebounds. Santarius (2015) shows that a micro-economic rebound analysis alone lacks “understanding of human behavior”. Santarius and Soland (2018) develop a comprehensive rebound typology from a behavioral science perspective and explain motivational rebound effects by the concepts of diffusion of responsibility, moral licencing, and attenuated consequences. In an experimental study, for example, it was shown that automation processes may impair personal responsibility for pro-environmental behavior (Murtagh et al., 2015). On the positive side, Santarius and Soland (2018) identify so-called beneficial effects, which countervail rebound effects. The authors explain the reduced preference for using a specific technology with the concepts of increased responsibility or improved control over frugal use (Santarius and Soland, 2018). Sometimes the energy demand during the manufacturing phase of products (`embodied energy') is referred to as an indirect rebound effect (Azevedo, 2014; Sorrell, 2007; Thomas and Azevedo, 2013). Font Vivanco and van der Voet (2014), on the other hand, see no methodological basis for considering embodied energy a rebound effect. The authors argue that any upstream resource demand is part of the production process and thus inseparable from the technology itself (Font Vivanco and van der Voet, 2014). In this article, the argumentation of Font Vivanco and van der Voet (2014) is followed, and embodied energy is assigned to first order effects.

In addition to rebound effects, induction effects may also increase resource demand, but are not directly attributable to efficiency gains (Hilty, 2008). Rather, the term 'induction effects' describes all the changes in user behavior that can be attributed to an increased choice of options (Walnum and Andrae, 2016). The induction effect is thus more general than the rebound effect (Røpke, 2012). A fundamental difference at the application level is important to emphasize: While optimization and substitution can be regarded part of higher order effects from a technological point of view, rebound/induction effects and beneficial effects are secondary consequences of this technological change and occur at the consumption and demand level. Macro scale higher order effects are concerned with structural changes of societies and economies e.g. through stimulation of economic growth or changing lifestyles and practices (Berkhout and Hertin, 2004; Horner et al., 2016). Also, rebound and induction effects can occur at the macro level. Since this paper focuses on higher order effects at the application level, these structural effects are excluded.

2.2. Environmental assessment approaches of technological change

For transformative technologies such as ICT, key factors affecting the results of the LCA include changes in efficiency and functionality, changes in infrastructure, changes in behavior, rebound effects or political and regulatory effects (Miller and Keoleian, 2015). At the same time, their inclusion in the assessment increases the uncertainty of the results. This applies in particular to user-related effects, such as behavior change or rebound effects (Miller and Keoleian, 2015). How these higher order effects can be assessed with LCA has been under discussion for a considerable time (Börjesson Rivera et al., 2014; Finkbeiner et al., 2014; Font Vivanco and van der Voet, 2014; Heijungs et al., 2009; Hertwich, 2005; Wolf and Chomkhamsri, 2015; Zamagni et al., 2008).

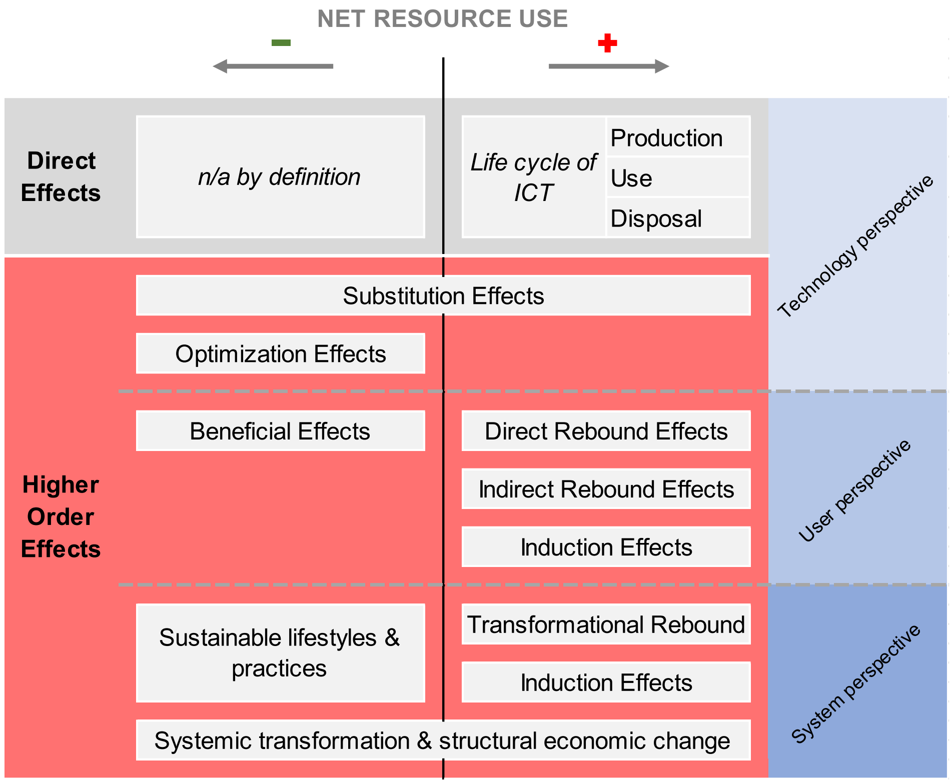

Fig. 1. Framework of environmental effects of ICT (own work, adapted from Aebischer and Hilty, 2015; Horner et al., 2016; Santarius and Soland, 2018).

The traditional attributional LCA (ALCA) method is defined in International Standards (ISO) and is designed for assessing all direct life cycle effects due to production, use and disposal of products and services (DIN EN ISO 14040, 2006). In addition to ALCA, various other types of LCA have now emerged. These complementary modelling approaches include sector-wide approaches, such as input-output LCA (IO-LCA), consequential LCA (CLCA), and other rather explorative modes of LCA, such as integrated LCA or scenario-based LCA (Finkbeiner, 2016; Guinée et al., 2018). What all LCA approaches have in common is their life cycle perspective. Differences exist with regard to the complexity of the situation to be modelled. Other methodological differences arise with regard to allocation rules, system boundaries or weighting methods (Finkbeiner, 2016; Guinée et al., 2018).

With regard to extending the environmental assessment towards higher order effects of technology replacement, one has to distinguish between the various effects introduced above. Technological change due to optimization of processes or substitution of technologies could be approached with comparative ALCA (DIN EN ISO 14040, 2006, p. 8). In the context of LCA studies, these effects are sometimes referred to as 'trade-off' (Bull and Kozak, 2014). Functional equivalence is a prerequisite here, i.e., the condition that the product "performs the same function" (DIN EN ISO 14040, 2006, p. 8). However, the product perspective of ALCA was criticized for preventing the integration of other higher order effects (Girod et al., 2011). Also, ISO does not give recommendations on how to cover any resulting secondary demand changes. The International Reference Life Cycle Data System (ILCD) handbook (European Commission, 2010, p. 187) however, proposes a consequential modelling approach for assessing higher order effects. Also Miller and Keoleian (2015) identify different modelling approaches for the various effects. While factors directly associated with the product or technology (efficiency changes, technology replacement) can be modelled with ALCA and CLCA, factors associated with the technology's interaction with the surrounding system (behavioral change, rebound effects) are typically addressed with CLCA (Miller and Keoleian, 2015).

Furthermore, approaches known as integrated LCA approaches may be relevant for the integration of higher order effects into the environmental assessment of ICT. Assuming that ALCA alone is unable to handle higher order effects (Börjesson Rivera et al., 2014; Finkbeiner et al., 2014; Finnveden et al., 2009), LCA is combined with methodologies from other fields in order to quantify and integrate higher order effects into the environmental assessment (Girod et al., 2011). These approaches can be roughly divided into economic models, scenario models and other deterministic models (Börjesson Rivera et al., 2014). Table 1 provides a compilation of higher order effects and corresponding LCA modelling approaches.

3. Methodology

The systematic literature research (SLR) was conducted following the approaches of Fink (2014) and Pickering and Byrne (2014). The final sample consists of case studies on the environmental assessment of higher order effects of ICT found via Web of Science, via supplementary research (Fischer et al., 2017) and via recommendation from a senior researcher in the field. The underlying research methodology, including research questions, keywords and inclusion criteria is summarized in Table 2 and explained in detail below.

After defining the research topic and research questions, keywords were selected. Combinations of the keywords 'ICT' and/or 'LCA' with synonyms for the term 'higher order effect' (indirect effect, rebound effect, second order effect, dematerialization, optimization) were used as search string. The research process can be described as an iterative research process. The initial sample was

Table 1
Higher order effects and corresponding modelling approaches in LCA.

Higher order effects	Approach	Level of analysis	References
Optimization	Comparative LCA (ALCA)	Application level	Herrmann et al. (2013)
Substitution	Comparative LCA (ALCA)	Application level	Bull and Kozak (2014)
	Advanced attributional LCA (ALCA)	Application and structural level	Andrae (2015)
Direct economic rebound	Marginal consumption (CLCA)	Application level	Thiesen et al. (2008)
	Consumption-as-usual (ALCA)	Application level	Girod et al. (2011)
	Macro IPAT-LCA	Structural level	Font Vivanco et al. (2014)
Indirect economic rebound	Consumption-as-usual (ALCA)	Application level	Girod et al. (2011)
Time rebound	Constant travel time budget	Application level	Spielmann et al. (2008)
Motivational rebound	Empirical results, scenario models	Application level	Polizzi di Sorrentino et al. (2016)
	Psychological rebound score	Application level	Madjar et al. (2006)

Table 2
Research methodology.

Topic	Environmental assessment of higher order effects of ICT with LCA
Research questions	- Which products and services are assessed? (RQ1) - Which higher order effects are considered? (RQ2) - How is the integration of higher order effects methodically realized? (RQ3)
Keywords	(i) ICT and/or; (ii) LCA and/or; (iii) indirect effect, rebound effect, second order effect, dematerialization, optimization
Search process and databases	- iterative search process - 3 search steps (Web of Science database, supplementary research (*bread-crumbing, pearl-growing*), input from a senior researcher in the field)
Inclusion criteria	- scope: LCA studies on environmental first order and higher order effects of ICT application - type of research: case studies and theoretical work - source: peer-reviewed journal articles - period of time: articles published between 2005 and 2018 - language: English
Exclusion criteria	- scope: no environmental framing, no ICT relation, no LCA methodology, only first order effects covered - type of research: reviews - source: conference articles, dissertations and technical reports - period of time: articles published before 2005 and after 2018 - language: any other language

compiled by searching the Web of Science database with the previously selected search strings. By repeatedly applying inclusion and exclusion criteria to titles/abstracts and full text, the initial sample was first narrowed down to the preliminary sample and then to the final sample. In addition, the preliminary sample was complemented by other relevant studies identified by supplementary research and recommendations. Criteria for exclusion were defined for the source (any other source than peer-reviewed journal articles, e.g. conference articles, dissertations), the scope, object and related impacts under study (only direct effects of ICT were considered, no ICT application, no environmental framing) and the methodological approach applied (does not apply attributional LCA or other special types of LCA). Furthermore, only studies from 2005 onwards were considered. This limitation resulted from the societal diffusion of ICT (Mallinson, 2015; Pfeiffer, 2017) and increased scientific reflection on its ecological effects (Horner et al., 2016; Murugesan, 2008; Williams, 2011) since the mid-2000s.

The initial sample consisted of 1,431 studies found via Web of Science. After a first practical screening by reading the titles and the abstracts, 42 relevant studies were included in the preliminary sample. 14 additional studies were identified via supplementary research and input from a senior researcher in the field and were added to the preliminary sample. The supplementary search was performed using the methods *bread crumbing* and *pearl growing* (Fischer et al., 2017) The reference sections of the pre-sample were checked for further relevant publications (*bread crumbing*). In a *pearl grow* search, further relevant studies that cited studies from the pre-sample were identified using citation databases. After detailed analysis of the full papers of the preliminary sample and the supplementary sample, the final sample consisted of 25 studies (see Fig. 2).

Two things are striking with regard to the final sample and will therefore be discussed in more detail. Compared to more than 1,000 first hits, only a small number of life cycle studies could be identified with SLR. In addition to a large number of studies from other research areas, many LCA case studies did not deal with higher order effects of ICT and therefore had to be excluded. Nevertheless, it was possible to identify 14 further studies through supplementary research. These studies met the SLR criteria but were not included in the initial sample. This can be traced back to the very diversified keywords of the additionally identified articles. It seems, however, that the thematic assignment to ICT services did not appear either in the title or in the keywords. Due to the high number of additional articles, there appears to be a clear limitation of the SLR. Although the search terms have been designed to include case studies from as many different areas as possible, it is possible that several case studies have been overlooked. Another limitation may be the authors' bias in applying exclusion criteria for the selection of all relevant studies.

4. Results

The final literature sample consisted of 25 papers (see compilation in Table 4). Almost all studies identified were published between 2010 and 2018, with peaks of six publications in 2015 and five publications in 2013. More than half of the studies identified were published in three journals only, namely the Journal of Cleaner Production (8 studies), the Journal of Industrial Ecology (5 studies), and the International Journal of Life Cycle Assessment (5 studies). The literature sample presented here differs in part from

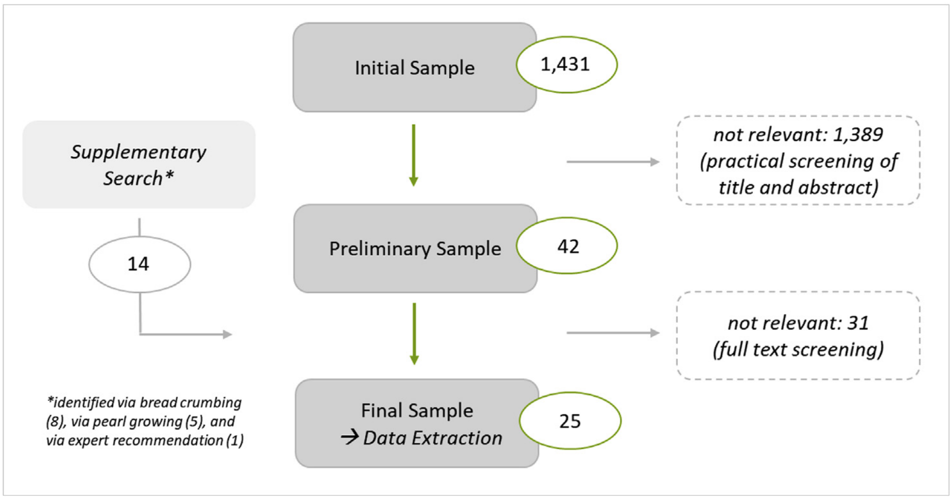

Fig. 2. Literature sample and screening methodology.

samples of earlier reviews in the field (Arushanyan et al., 2014; Bieser and Hilty, 2018; Frehe and Teuteberg, 2014; Horner et al., 2016; Jeswani and Azapagic, 2015; Yi and Thomas, 2007) due to partial differences in research questions and search criteria. In the following, the literature sample will be analyzed according to thematic and methodological characteristics. The analysis is mainly based on the previously introduced framework of environmental effects of ICT shown in Fig. 1. The structure is based on the research questions introduced in section 1. The results for all studies are also summarized in Table 4.

4.1. ICT services under study

The studies can be assigned thematically to four different types of ICT-based services: (i) e-materialization, (ii) telework, (iii) e-commerce, and (iv) monitoring and control. The classification of ICT services used here is frequently used in the literature (Berkhout and Hertin, 2004; Horner et al., 2016). The definitions of the different services according to Horner et al. (2016) are adopted in the following. As shown in Fig. 3, most of the studies were directly focused on e-materialization processes. The majority of these studies examined the substitution of traditional by digital media. Two studies investigated one of the simplest forms of media substitution, the switch from manual delivery of documents to electronic delivery. Mirabella et al. (2013) compared forms of traditional and digital management of documents in public administration. Moberg et al. (2010a) investigated the environmental effects related to the conversion from paper invoices to electronic invoices. Other studies compared print products, such as magazines, newspaper and books with their digital equivalents. Although the object of investigation seems quite similar, the studies differ in terms of functional units and scope. Achachlouei and Moberg (2015) compared the print and tablet editions of a Swedish magazine. In another study, Moberg et al. (2010b) compared a printed newspaper with an e-newspaper read on a tablet. Amasawa et al. (2018) and Moberg et al. (2011) compared reading an e-book with reading a paper book.

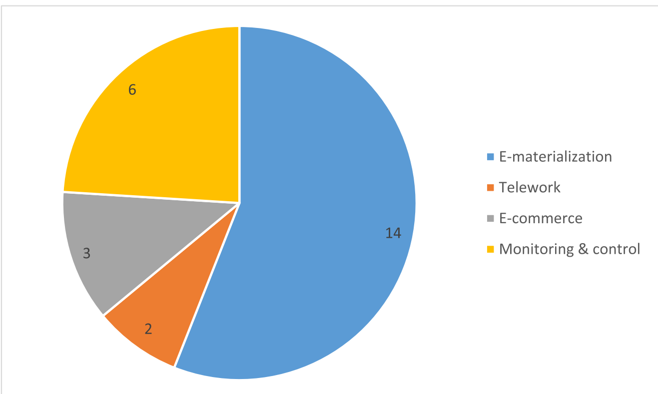

Fig. 3. Share of publications by ICT service under study.

Furthermore, media consumption of movies or music via CD/DVD/Blu-ray was compared with downloading or streaming: Shehabi et al. (2014) analyzed video viewing through both traditional DVD and online video streaming. Weber et al. (2010) compared music delivery by digital download with shipment of a CD. Mayers et al. (2015) investigated different ways of games distribution: Blu-ray discs delivered by retail stores vs. game files downloaded. Particularly noteworthy are those studies investigating the effects of e-materialization within the ICT sector. Andrae (2013) compared the office usage of physical desktops with virtual desktops in a cloud network. In another study, Andrae (2015) investigated the environmental effects when certain mainly electronic devices were replaced by smartphones. Maga et al. (2013) compared server-based computing in combination with thin clients with a typical desktop PC workplace. Hochschorner et al. (2015) compared the environmental effects of online movie distribution by download and streaming. Subramanian and Yung (2017) analyzed all-in-one personal computers in comparison to desktop computers.

All other studies examined ICT effects in the areas of monitoring and control, e-commerce and telework. Studies examining monitoring and control services with sensors and ICT infrastructure focused on waste management, energy management and production processes. Compared to a conventional collection system, Lelah et al. (2011) investigated a machine-to-machine enhanced product service system for the collection of waste glass, in which the collection routes were planned on the basis of real-time data on how full the collection containers were. Bonvoisin et al. (2014) analyzed the environmental implications of a municipal waste collection system based on a city-scale wireless sensor network. Gangolells et al. (2015) investigated the environmental effects of the implementation of a smart autonomous control of ventilation, lighting and vertical transportation, implemented in a representative underground station of the Barcelona metro network. Scheepens and Vogtländer (2018) compared the installation of insulation with smart temperature control for domestic heating savings. van Dam et al. (2013) analyzed energy management systems with regard to their net energy savings. Cerdas et al. (2017) compared a 3D printing-supported manufacturing system with a conventional manufacturing system.

With regards to e-commerce, Borggren et al. (2011) investigated the environmental effects of a paper book bought in a traditional bookshop with one bought via an internet bookshop. Sivaraman et al. (2007) compared traditional vs. e-commerce DVD rental services. van Loon et al. (2015) compared online and conventional retailing of fast moving consumer goods.

Finally, case studies on telework focused on business and conference meetings. Borggren et al. (2013) compared different types of business meetings requiring travel (by car, aviation or train) with mediated business meetings (connected via PC at the workplace, or in an additional meeting room with different technical equipment). Coroama et al. (2012) analyzed the environmental effects of Internet-based multiple-site conferences compared to traditional conference settings.

4.2. Consideration of ICT effects of higher order

The classification of all selected studies according to the ICT effects under consideration (Fig. 4) shows that the substitution, optimization and, in some cases, also rebound and induction effects were taken into account.

The starting point of each of the studies was the comparison of two or several product systems (often referred to as ‘traditional’ vs. ‘digital’/‘innovative’/‘online’). Thus, the higher order ICT effects aimed at were substitution and optimization effects. The analysis shows that, depending on the ICT service, these two technology-based effects are usually included within the system boundaries.

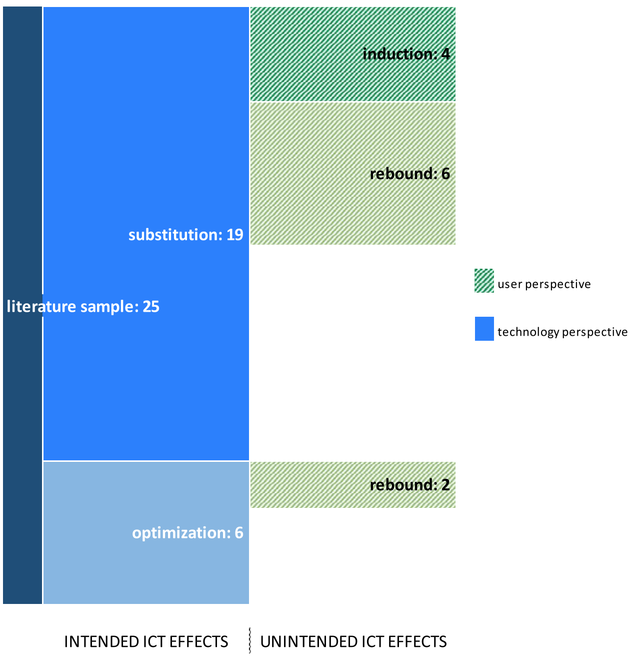

Fig. 4. Higher order effects considered in the literature sample and corresponding number of studies.

Most studies deal with substitution processes, but some studies also analyze optimization processes. This also corresponds to the aforementioned assignment to certain ICT services, where optimization is the intended ICT effect for monitoring and control services, while the ICT effect for e-materialization, e-commerce and telework is substitution (of products or product systems).

In addition, some of the studies on substitution effects included other (probably unintended) higher order ICT effects due to changed use patterns. Some studies took rebound effects into account (Amasawa et al., 2018; Andrae, 2013; Borggren et al., 2013; Coroama et al., 2012; Moberg et al., 2010a; Weber et al., 2010). Studies focusing on telework examined the environmental impact of rebound effects, which can be seen in an increased number of mediated meetings compared to business meetings that require travel (Borggren et al., 2013) or in an increased number of participants at a conference location requiring less travel effort (Coroama et al., 2012). One study examining the e-materialization effect of ICT included different degrees of direct rebound effects resulting from improving energy efficiency by switching from physical to virtual desktops (Andrae, 2013). Another study comparing paper book and e-book reading analyzed the rebound effect resulting from increased e-book reading activities (Amasawa et al., 2018). Other studies investigated rebound effects resulting from online document access and the ensuing printing of documents (Moberg et al., 2010a) or the burning of downloaded music to CD (Weber et al., 2010). However, it is not clear whether the latter effects can actually be classified as a rebound effect. Berkhout and Hertin (2004) use a similar example to describe rebound effects of ICT use. In contrast, Börjesson Rivera et al. (2014) use the term “rematerialization” in the same sense independently from rebound effects.

Additionally, studies on the substitution effects of media devices also considered induction effects (Achachlouei and Moberg, 2015; Andrae, 2015; Hochschorner et al., 2015; Moberg et al., 2010b). In three studies, the induction effect considered was the overall change of each electronic device's use time due to the device's availability (Achachlouei and Moberg, 2015; Hochschorner et al., 2015; Moberg et al., 2010b). Andrae (2015) considered an induction effect of additionally purchased ICT devices when substituting other devices with a smartphone. Overall, no substitution study was found that included more than two ICT effects of higher order in the assessment.

Rebound effects were also considered in some studies on optimization effects, by assuming increased demand of 3D printed products (Cerdas et al., 2017), or by taking into account that saved money may be spent for other purposes (Scheepens and Vogtländer, 2018). Additionally, the studies by Bonvoisin et al. (2014) and Lelah et al. (2011) are worth mentioning. Both studies applied an iterative assessment process aimed at avoiding impact shifting and rematerialization from the implementation of ICT equipment. However, with regard to the framework of ICT effects (Fig. 1), rematerialization is to be assigned to direct effects of ICT. Therefore, the rematerialization effect is not further considered here.

4.3. Methodological considerations

All case studies presented above are based on specific methodological considerations, which will now be analyzed according to selected methodological characteristics. In particular, it will be considered which specific approaches were applied for the integration of higher order effects, which types of impacts were considered in the assessment and which overall methodological approach was chosen.

4.3.1. Integration of higher order ICT effects

The methodological options chosen for integrating higher order ICT effects into a LCA were further analyzed. The following five approaches (i) comparative study design, (ii) sensitivity analysis, (iii) scenario modelling, (iv) allocation, and (v) customized modelling were identified.

Substitution and optimization effects were generally included in all studies through a comparative study design. Since these effects are based on a product system level, either a digitalized product system was compared with a traditional reference system or various other scenarios or reference systems from previous studies were used. The methodological integration of rebound effects and induction effects was realized by sensitivity analysis, scenario modelling, allocation, and customized modelling. The summary is shown in Table 3.

Sensitivity analysis is defined by ISO as a "systematic procedure for estimating the effects of the choices made regarding methods and data on the outcome of a study" (DIN EN ISO 14040, 2006) and is used to identify individual data uncertainties within a model (Huijbregts et al., 2001). Achachlouei and Moberg (2015) and Hochschorner et al. (2015) used sensitivity analysis to identify the impact of induction effects on the overall results (changed reading time of a tablet edition of a newspaper and of the increasing overall use time of a tablet; reduced bandwidth when uploading and downloading a movie because of simultaneous work). Moberg et al. (2010a) determined the environmental relevance of a potential rebound effect (different ways of handling electronic invoices).

Scenario modelling in LCA studies is used to describe "a possible future situation relevant for specific LCA applications, based on specific assumptions about the future" (Pesonen et al., 2000) and is used to investigate uncertainties regarding the chosen model (Huijbregts, 1998). What-if scenarios, with which the environmental impacts of several options within a system can be studied, can be cited as one of the basic scenario approaches (Pesonen et al., 2000). Andrae (2013) analyzed the environmental effects for different rebound effect scenarios caused by switching from physical to virtual desktops. Weber et al. (2010) analyzed a series of scenarios for the delivery of one music album. In one of the scenarios, rebound effects were taken into account by assuming a different handling of downloaded music. Cerdas et al. (2017) also calculated a rebound effect by assuming a shorter lifetime and faster substitution of an eyeglass frame in one scenario. Other studies also took a similar approach: Borggren et al. (2013) took rebound effects into account by assuming an higher annual number for mediated business meetings in one scenario, as did Coroama et al. (2012), who assumed a different number of conference participants in the alternative scenarios.

Another approach was taken by Moberg et al. (2010b). The authors refrained from using scenarios or conducting a sensitivity analysis. Instead they integrated an induction effect directly into their model by assuming an increased overall use time of the tablet. In contrast to the other approaches, the impact of changed usage behavior on the result was not examined by uncertainty analysis. Rather, changed use patterns were directly modelled using allocation. Amasawa et al. (2018) took a similar approach by integrating the rebound effect of e-book reading activities directly into their model. On the basis of an online survey, the authors calculated that the group using an e-book reader purchased significantly more books than the others.

Andrae (2015) and Scheepens and Vogtländer (2018) chose a similar approach. They both directly integrated rebound and induction effect into customized models by means of mathematical calculation. Scheepens and Vogtländer (2018) calculated potential indirect rebound effects after the payback period of an energy management system. Andrae (2015) took induction effects into account by including other devices such as laptops and tablets into the model in addition to the smartphone.

The data used to integrate higher order effects into the assessment is a crucial aspect of the methodology. For the integration of technology-based ICT effects, such as substitution and optimization, existing technical data was used or collected manually. The data basis was different for the integration of user-related effects by means of sensitivity analysis, scenario modelling, mathematical calculation and allocation. In few studies, the modelling of higher order effects was based on surveys among participants (Amasawa et al., 2018; Coroama et al., 2012) or based on market data (Andrae, 2015). The potential rebound and induction effects of all other studies were formed solely on the basis of assumptions.

4.3.2. Environmental impacts considered

The environmental impact categories covered in the literature sample were further analyzed (see Fig. 5). The results ranged from a single impact category to up to 15 different impact categories.

Only some studies assessed the environmental impact in a comprehensive set of (up to 15) impact categories (Achachlouei and Moberg, 2015; Borggren et al., 2011; Cerdas et al., 2017; Gangolells et al., 2015; Lelah et al., 2011; Mirabella et al., 2013; Moberg et al., 2011, 2010b; Sivaraman et al., 2007; Subramanian and Yung, 2017). More than half of all studies focused on only one or two impact categories. Mostly, global warming potential was assessed,

Table 3
Methodological integration of rebound effects and induction effects into LCA and corresponding studies.

Effect \ Approach	Sensitivity analysis	Scenario modelling	Allocation	Customized modelling
Rebound effect	Moberg et al. (2010a)	Andrae (2013),[3] Borggren et al. (2013), Cerdas et al. (2017), Coroama et al. (2012), Weber et al. (2010)	/	Scheepens and Vogtländer (2018)
Induction effect	Achachlouei and Moberg (2015), Hochschorner et al. (2015)	/	Amasawa et al. (2018), Moberg et al. (2010b)	Andrae (2015)

Table 4
Summary of methodological considerations of LCA studies considering higher order effects of ICT (Impact categories abbreviations are: GHG – greenhouse gases, RMD – raw material depletion, MIPS – material input per unit of service).

Study	ICT service under study	Functional Unit	Impact categories	Type of LCA	ICT effects					Integration of unintended ICT effects (data basis)
					Direct	Optimization	Substitution	Rebound	Induction	
Achachlouei and Moberg (2015)	E-materialization	One reader's use of one copy of Skona Hem (basic FU); 1 hour of reading/1 copy of the magazine (additional FU)	Several	ALCA	■		■		■	Sensitivity analysis (assumption on average use)
Amasawa et al. (2018)	E-materialization	Book reading activities per person and per person-book	GHG	Screening ALCA	■		■	■		Allocation (online survey and social experiment)
Andrae (2013)	E-materialization	The potential annual usage of 488 workers performing daily computing tasks in a „global" office"	Energy, GHG	ALCA, CLCA	■		■	■		Scenario modelling (theoretical calculation of results, formula)
Andrae (2015)	E-materialization	Annual personal device usage of one individual	GHG	Advanced ALCA	■		■		■	Mathematical calculation (market based marginal data on product mixes)
Bonvoisin et al. (2014)	Monitoring & control	Centralized ten-year hourly provision of glass-level values for all the waste glass containers in Grenoble	RMD, GHG	ALCA	■	■				
Borggren et al. (2011)	E-commerce	One book bought and read by one person	Several	Screening ALCA	■		■			
Borggren et al. (2013)	Telework	One three-hour business meeting (ALCA); consequence of replacing some of the conventional business meetings with mediated meetings during one year (CLCA)	Energy, GHG	ALCA, CLCA	■		■	■		Scenario modelling (theoretical assumption)
Cerdas et al. (2017)	Monitoring & control	Provision of one eyeglass frame at the point of sale	Several	ALCA			■	■		Scenario modelling (theoretical assumption)
Coroama et al. (2012)	Telework	n/a	GHG	Screening ALCA			■	■		Scenario modelling (online survey)
Gangolells et al. (2015)	Monitoring & control	Manufacturing and usage of an energy management system over its lifetime (with 5-year and 10-year lifetime scenarios)	Several	ALCA	■	■				
Hochschorner et al. (2015)	E-materialization	Distributing and watching a movie (here defined as 2 h and 3 GB)	GHG	Screening ALCA	■		■		■	Sensitivity analysis (allocation, assumption: 50% of the active energy use of the laptop was allocated to the movie and the other 50% to the other activities performed)
Lelah et al. (2011)	Monitoring & control	Collecting waste glass in the Voiron County over the course of ten years	Several	ALCA	■	■				
Maga et al. (2013)	E-materialization	Supply of a computer workstation with two or three applications simultaneously for a time period of 5 years with 220 working days per year	GHG, MIPS	MEErP	■		■			
Mayers et al. (2015)	E-materialization	Distributing and playing a video game (8.8 GB); delivering content via Internet and Blu-ray disc	GHG	ALCA	■		■			
Mirabella et al. (2013)	E-materialization	Number of forms managed in one year for the three types of procedures, i.e. 2132 in 2008	Several	ALCA	■		■			
Moberg et al. (2010b)	E-materialization	Consumption of a newspaper during one year by one unique reader	Several	Screening ALCA	■		■		■	Allocation (assumption: 30 min e-newspaper, 30 min other purposes)
Moberg et al. (2010a)	E-materialization	The total amount of invoices in Sweden over the course of a year:	Energy, GHG	Screening ALCA	■		■	■		

		'The distribution of 1.4 billion invoices, whereof 70% B-to-C and 30% B-to-B'							Sensitivity analysis (assumption: all electronic invoices will be printed by users)
Moberg et al. (2011)	E-materialization	One specific book bought and read by one person	Several	Screening ALCA	■		■		
Scheepens and Vogtländer (2018)	Monitoring & control	Living area	Other	EVR	■	■		■	Mathematical calculation (eco-cost/value ratio tables for EU)
Shehabi et al. (2014)	E-materialization	n/a	Energy, GHG	CLEER model	■		■		
Sivaraman et al. (2007)	E-commerce	Renting three DVDs at one time	Several	Hybrid LCA	■		■		
Subramanian and Yung (2017)	E-materialization	A HP Omni 120-2-28hk All-in-one PC and a conventional desktop PC that weighs 14 kg and consists of desktop computer monitor, LCD flat screen, keyboard and the mouse	Several	ALCA	■	■			
van Dam et al. (2013)	Monitoring & control	n/a	Energy	Screening ALCA	■	■			
van Loon et al. (2015)	E-commerce	Acquisition and fulfilment of one consumer item	GHG	Screening ALCA	■		■		
Weber et al. (2010)	E-materialization	One album of music	Energy, GHG	n/a	■		■	■	Scenario modelling (assumption of six different scenarios)

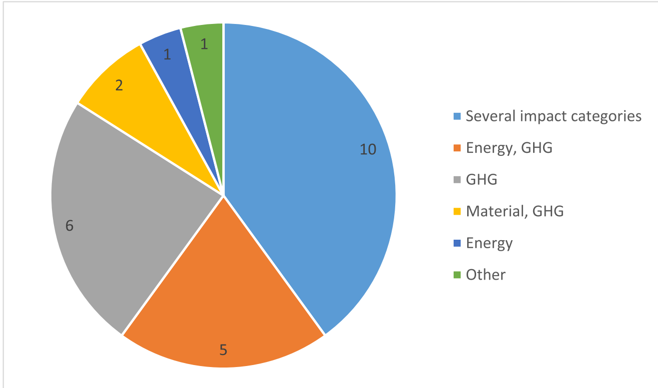

Fig. 5. Environmental impact categories covered in the sample and corresponding number of studies.

usually in combination with energy demand (e.g. Borggren et al., 2013; Moberg et al., 2010a) or material demand/material depletion (Bonvoisin et al., 2014; Maga et al., 2013). van Dam et al. (2013) assessed only cumulative energy demand. Other studies focused only on carbon footprint (e.g. Coroama et al., 2012; Mayers et al., 2015). One study used a monetized single indicator (Scheepens and Vogtländer, 2018).

Furthermore, the studies were compared based on their impact assessment methods. ReCiPe and CML were mainly used in studies analyzing several impact categories. Studies focusing exclusively on global warming potential and/or energy demand mainly used GWP100 (IPCC, 2007) for assessing GHG emissions. Cumulative energy demand was assessed using the method of Frischknecht et al. (2007).

4.3.3. Methodological approaches

The choice of overall methodological approaches was analyzed further. The approaches (i) ALCA, (ii) screening ALCA, (iii) combination of ALCA and CLCA, (iv) hybrid LCA and (v) customized model were identified. Results are shown in Fig. 6.

For the vast majority of studies an attributional LCA (ALCA) approach was chosen. That approach was further divided into full ALCA studies and screening ALCA studies, whereby the term "screening LCA" was taken from studies of Moberg et al. (2011, 2010a, 2010b). The difference between the two approaches is the

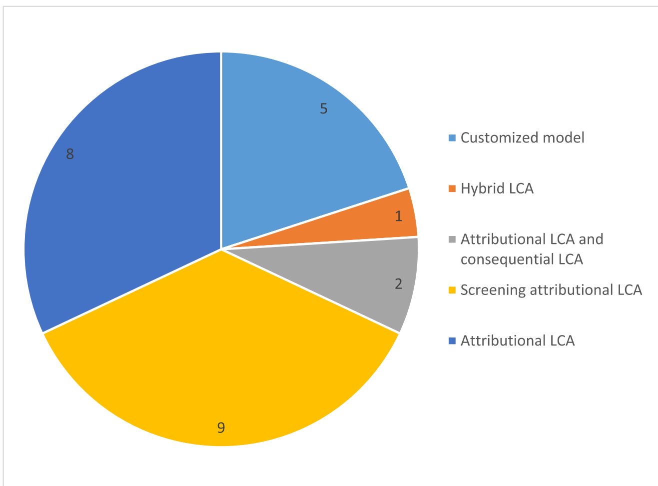

Fig. 6. Different LCA approaches and corresponding number of studies.

type of data used. For screening ALCA studies, data quality is less important, as the aim is to identify the most relevant processes of the system under study. This is why mostly readily available data from databases is used (Moberg et al., 2010a). In contrast, data origin and data quality are crucial in full ALCA studies (DIN EN ISO 14040, 2006). Therefore, all studies that solely used databases were classified as "screening LCA studies" in the following analysis.

Two studies used a combination of ALCA and CLCA (Andrae, 2013; Borggren et al., 2013). For both studies an attributional approach was chosen, which was supplemented by a consequential part. Andrae (2013) compared the effects on GHG emissions from the use of physical desktops and virtual desktops for different electricity mixes (attributional electricity mix, consequential marginal electricity mix). Borggren et al. (2013) studied the consequences of replacing travel with mediated meetings using consequential assessments.

In one study a hybrid LCA approach was chosen. Sivaraman et al. (2007) used a hybrid LCA combination of process-based and input-output LCA methods to obtain the environmental impact of a traditional vs. an e-commerce DVD rental service. For the hybrid LCA approach as used by Sivaraman et al. (2007), information from two databases (Simapro, economic input-output life-cycle assessment) was combined.

The remaining studies could not be assigned to any of the aforementioned methods and were summarized as "customized models". Four studies used specific models based on the LCA methodology: Andrae (2015) developed "advanced ALCA", a method based on ALCA that includes also market effects. Maga et al. (2013) applied the "methodology for ecodesign of energy-related products" (MEErP) that was developed on behalf of the European Commission (European Commission, 2011). Scheepens and Vogtländer (2018) applied the method of eco costs/value ratio (EVR) to analyze the costs, the market value and the eco-costs of a product (Vogtländer et al., 2002). Shehabi et al. (2014) used the Cloud Energy and Emission Research (CLEER) model that was developed for the environmental assessment of cloud services in different regions (Masanet et al., 2013). Only the study by Weber et al. (2010) did not provide any further information on the methodological approach. Studies in which rebound effects and induction effects were included in the assessment usually chose an ALCA approach (Achachlouei and Moberg, 2015; Cerdas et al., 2017) or screening ALCA approach (Amasawa et al., 2018; Coroama et al., 2012; Hochschorner et al., 2015; Moberg et al., 2010b, 2010a). In addition, higher order effects were also included in the consequential parts of the studies by Andrae (2013) and Borggren et al. (2013) and in the customized models by Andrae (2015) and Scheepens and Vogtländer (2018).

Furthermore, the studies were compared based on LCA software and databases used. Most studies used SimaPro, few studies used GABI (Moberg et al., 2010b), Umberto (Cerdas et al., 2017) and customized LCA modelling software (Bonvoisin et al., 2014; Lelah et al., 2011; Maga et al., 2013; Shehabi et al., 2014). The ecoinvent database was used in almost all studies. Few studies used other databases such as ELCD database (Achachlouei and Moberg, 2015), EIME database (Bonvoisin et al., 2014; Lelah et al., 2011), and EIOLCA (Sivaraman et al., 2007). However, some studies did not indicate which software and databases were used (Andrae, 2015; Coroama et al., 2012; Mirabella et al., 2013; van Dam et al., 2013).

5. Discussion

In the following paragraphs, the main findings will be highlighted and discussed concerning methodological considerations and limitations. On that basis, a proposal for future research needs is derived from the identified research gaps.

5.1. ICT services under study

Thematically, studies examined the environmental impacts of ICT applications and ICT services in the areas of e-materialization, telework, e-commerce and monitoring and control. However, most studies were concerned with the environmental effects of the substitution of certain media with electronic devices or digital services. Only a few case studies investigated the environmental effects of ICT services in e-commerce, telework and monitoring and control. In addition, there is a lack of LCA studies of higher order effects of ICT services in other sectors such as production/industry, agriculture or (public) transportation. Overall, the literature sample thus presents an incomplete picture of digitalization. Especially in the latter areas, the digital transformation can be seen in many cases. Furthermore, most studies took a more product-focused approach. Only a few studies analyzed ICT-based services/product service systems such as waste collection (Bonvoisin et al., 2014; Lelah et al., 2011), reading books (Achachlouei and Moberg, 2015; Amasawa et al., 2018; Moberg et al., 2011), watching movies (Shehabi et al., 2014) or telework (Borggren et al., 2013; Coroama et al., 2012). A more comprehensive picture of the environmental impact of digitalization does require a stronger focus on services/product service systems. In addition to the aforementioned services, services involving sharing and renting should also be investigated. Overall, due to their thematic focus, the case studies examined here allow only limited conclusions to be drawn about the environmental impact of digitalization.

5.2. Consideration of ICT effects of higher order in LCA

The premise of all 25 studies was the analysis of the environmental impacts of technological change. The focus was on replacing an original, mostly non-digital product system with a digitalized system or on optimizing the system with ICT devices. In this sense, all studies mainly considered ICT effects of higher order from a technological point of view, namely substitution and optimization. Only few studies were found which tried to assess the environmental impact of ICT applications from a more comprehensive perspective, including both changes in technology and use patterns. One of the reasons for the limited consideration of user-related ICT effects can be clearly seen in general LCA practice, where changes in user behavior are typically ignored (Hellweg and i Canals, 2014; Polizzi di Sorrentino et al., 2016; Shahmohammadi et al., 2018). With regard to user-related higher order effects, types of rebound effects and induction effects were included in the assessment in some studies. The rebound effects considered can be classified into (i) direct rebound effects related to increased use due to cost and time reduction (Amasawa et al., 2018; Andrae, 2013; Borggren et al., 2013; Cerdas et al., 2017; Coroama et al., 2012; Scheepens and Vogtländer, 2018) and (ii) usage behavior other than expected (Moberg et al., 2010a; Weber et al., 2010). Studies considering an induction effect took into account increasing overall use time of the electronic device under study (Achachlouei and Moberg, 2015; Hochschorner et al., 2015; Moberg et al., 2010b) and acquisition of additional electronic devices (Andrae, 2015). Often the aforementioned effects were not labelled in the case studies as rebound effects or induction effects, but were subsequently identified as such by the authors of this review. This suggests that some of the case studies' authors were not familiar with the existing frameworks of environmental effects of ICT. However, the lack of income rebound effects or induction effects is described as a limiting factor in some case studies (Shehabi et al., 2014; Weber et al., 2010). Besides, other types of rebound effects are also noticeable that were only considered in few or no studies, such as time rebound, space rebound or motivational rebound. Depending on the system under study, these effects could have been taken into account in some studies, e.g. time rebound effects when streaming films, space rebound effects with media substitution or motivational rebound effects when implementing energy management systems. As already pointed out by Börjesson Rivera et al. (2014), both the inclusion and the exclusion of higher order effects of ICT in the assessment is a methodological and contextual decision that can have an influence on the overall result and should therefore ideally be made transparent. Furthermore, the selection of the respective effects depends on the specific research question (Miller and Keoleian, 2015).

5.3. Integration of ICT effects of higher order in LCA

Depending on the respective ICT effect, several approaches for integration in LCA were identified. For the technically based ICT effects of substitution and optimization, a comparative study design was chosen in which a traditional product system was compared with its digitalized equivalent. In this context, the comparability of product systems with regard to functional equivalence (DIN EN ISO 14040, 2006; European Commission, 2010) and the handling of multifunctionality (Hischier and Reichart, 2003; Kim et al., 2017) in LCA are important issues that must be taken into account. Functional equivalence was addressed in several case studies focusing on the substitution of media (Achachlouei and Moberg, 2015; Moberg et al., 2011, 2010a; 2010b; Shehabi et al., 2014; Weber et al., 2010), on telework (Borggren et al., 2013; Coroama et al., 2012), on e-commerce (Sivaraman et al., 2007), and on monitoring and control (Cerdas et al., 2017; Scheepens and Vogtländer, 2018). Multifunctionality was discussed with regard to the functional equivalence of ICT devices compared to printed products (Achachlouei and Moberg, 2015; Amasawa et al., 2018; Moberg et al., 2011, 2010a).

For the integration of rebound effects and induction effects, sensitivity analysis and scenario modelling were primarily used. Both modelling approaches are part of uncertainty analysis in LCA. With regard to the user-related effects of induction and rebound, the objective was to estimate the influence of a changed use phase on the overall result. Few studies used customized approaches to integrate rebound and induction effects. The question of how these effects can be methodically integrated into LCA thus touches on the one hand the aforementioned debate about handling different usage behavior in LCA practice (Hellweg and i Canals, 2014; Polizzi di Sorrentino et al., 2016; Shahmohammadi et al., 2018), and other methodological decisions, such as the definition of system boundaries or a functional unit (Kim et al., 2017; Kjaer et al., 2016). On the other hand, it also relates to the question of a valid data basis. As the analysis results show, only a few studies used surveys (Amasawa et al., 2018; Coroama et al., 2012) or market data (Andrae, 2015) to estimate rebound effects and induction effects. The modelling of rebound effects and induction effects in all other studies was solely based on assumptions, e.g. about the overall use times of devices and increased or varying use of products and services. For a more realistic approach, Polizzi di Sorrentino et al. (2016) call for greater involvement of behavioral science in LCA modelling. Daae and Boks (2015) also propose additional methods such as expert interviews, measurements or simulations.

5.4. Environmental impacts

It was found that more than half of all studies focused on only one or two impact categories. The limitation of many studies to only a few environmental impact categories has been discussed in some of the studies (Bonvoisin et al., 2014; Borggren et al., 2013; Moberg et al., 2010a; van Loon et al., 2015). The reasons given were simplification, effort and relevance. For ICT in particular, another reason for concentrating on just a few impact categories could be limited access to relevant inventory data (Finkbeiner et al., 2014; van Capelleveen et al., 2018). In addition, a partial environmental impact assessment may also increase the risk of overlooking impact shifting, as shown by Bonvoisin et al. (2014) and Lelah et al. (2011). In order to avoid not only burden shifting but also problem shifting from one life cycle phase to another, a comprehensive impact assessment over the entire product life cycle is important (Finnveden et al., 2009).

5.5. Methodological approaches

The review conducted here found almost solely studies in which ALCA or ALCA-based approaches were used. This shows once again that the integration of rebound effects and other higher order effects into ALCA approaches is generally feasible. Compared to the selection of modelling approaches presented in section 2, it is striking that almost no other modelling approaches, e.g. addressing indirect rebound effects of ICT with CLCA (Ekvall, 2002), could be identified in the present review. The choice of assessment methods and the effects under consideration are interdependent, as they are both linked to the study scope and goal. As already described in the section above, only a limited number of higher order effects were addressed in the studies. This may be due to the fact that, depending on the scope of the higher order effects, it may be difficult with ALCA to reflect dynamic changes and to depict overlapping effects of consumption and technology (Guinée, 2002; Ryen et al., 2015). Therefore, it is also important to address the limits of LCA (Guldbrandsson and Bergmark, 2012). In addition, other methods such as agent-based modelling or system dynamics may be more suitable for modelling structural environmental impacts of ICT (Bieser and Hilty, 2018). However, as complexity increases, uncertainties increase accordingly and need to be addressed (Baustert and Benetto, 2017; Bull and Kozak, 2014; Williams et al., 2009). Baustert and Benetto (2017) propose an extended classification of potential sources into parameters uncertainty, uncertainty due to choices, structural uncertainty and systemic variability. Due to variability in human decisions, systemic variability in particular is a potential source of uncertainty in complex modelling approaches. It could, for example, be taken into account by using multiple simulations (Baustert and Benetto, 2017; Bruch and Atwell, 2015). Similarly, Bornhöft et al. (2016) show the handling of uncertainties when conducting a Material Flow Analysis.

5.6. Proposal of a future research agenda

In the following section, the research gaps identified in previous sections are summarized and a proposal for future research needs for assessing higher order effects of ICT application is derived.

The literature analysis revealed research gaps with regard to both the thematic range of the ICT services and effects examined and to the methodological integration of effects of higher order into LCA. Most studies investigated the substitution of certain media with electronic devices or digital services. Studies on environmental effects of ICT processes and services in areas other than media substitution are still weak. Furthermore, only a few studies focused on investigating product service systems. The rather product-oriented focus is also reflected in the type of higher order effects considered. Primarily technically-based effects such as substitution and optimization were investigated. Not only were user-related ICT effects less frequently integrated into the assessment, but many behavioral effects, such as time rebound, space rebound or motivational rebound, were not taken into account.

From a modelling perspective, only a few approaches, namely comparative study design, uncertainty analysis, allocation and customized approaches, were used to integrate higher order effects of ICT into LCA. Limitations were also found for the number of impact categories under consideration as well as for the methodological approaches applied.

This results in the following proposals for future research, with the aim of better understanding the potential of ICT applications for sustainability.

ICT as a transformative technology has the potential to fundamentally change society, the economy and lifestyles. This should be reflected in the choice of research objects, research questions and the definition of the goal and scope of future studies. The understanding of the challenges and the necessary methodological developments would benefit from more case studies, especially in thus far scarcely covered areas like housing, production, agriculture or transportation. Also, the environmental effects of product service systems, such as sharing or renting, should be increasingly investigated.

It is well understood that the introduction of new technologies, their optimization and substitution also change user behavior. For realistic modelling of ICT applications in LCA, it is important to take into account different usage behavior. This includes rebound effects and induction effects. There are already several modelling approaches for their integration, as shown in this study. However, further studies should develop interdisciplinary approaches to address the multitude of user-related effects and other secondary effects of technological change in LCA. In particular, the stronger involvement of behavioral sciences in use phase modelling appears to be promising, also with regard to the collection of current usage data.

In addition, based on a solid attributional assessment, additional scenarios to include dynamic and infrastructural effects into LCA, through macroeconomic scale-up or consequential approaches, could also be assessed. Such combined approaches could also be increasingly used in the field of digitalization, in order to examine environmental effects of increasing ICT application from a complementary point of view.

In terms of good LCA practice it is important to emphasize that a comprehensive impact assessment should be performed over the entire product life cycle. Furthermore, issues such as comparability, multifunctionality, data quality, uncertainty and transparency should be addressed more frequently. The focus of the analyses was exclusively on ICT and should be extended to other transformative technologies in the future.

6. Conclusion

The aim of this review was to provide a methodological overview of existing approaches for integrating ICT effects of higher order into LCA case studies. This paper thereby examined which products and services were assessed, which and how ICT effects of higher order, namely optimization, substitution, rebound and induction effects were integrated into LCA case studies of ICT application, and which overall methodology was chosen. Studies focused mainly on the substitution of certain media with electronic devices or digital services. Few other case studies were concerned with the environmental effects of the introduction of ICT services in commerce, telework and monitoring and control. The results show that the premise of all studies was to analyze the environmental impact of technological change. All studies considered the technology-based ICT effects of substitution and optimization, while few studies considered resulting changes in use patterns. Overall, the analysis of technology-based effects clearly predominated. The results presented here also show that there exist conventional approaches, such as comparative study design, scenario modelling and sensitivity analysis, to integrate higher order ICT effects into LCA case studies. In order to better understand the potential of digitalization for sustainability three key conclusions for future research can be drawn from these analyses: Firstly, LCA case studies should increasingly address ICT services in areas such as housing, transportation or production. Practices such as sharing or renting also need to be further analyzed. Secondly, for realistic modelling of ICT applications in LCA, it is important to take into account different usage behavior. Interdisciplinary approaches ought to be developed to integrate rebound effects and induction effects into LCA. Thirdly, for a more accurate modelling of user behavior the collection of use-related data should also be put on solid methodological basis, e.g. by using supplementary methods such as surveys.

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3.2 The integration of higher-order effects of ICT into LCA - conceptual framework

In this section a conceptual framework for integrating the higher-order effects of ICT into LCA is presented and applied in a first case study. This section contains the following publication:

Pohl, J., Frick, V., Höfner, A., Santarius, T., Finkbeiner, M., 2021. Environmental saving potentials of a SHS from a life cycle perspective: How green is the smart home? Journal of Cleaner Production 312, 127845. https://doi.org/10.1016/j.jclepro.2021.127845

Supplementary material to this publication is provided in the Appendix of this thesis.

CRediT author statement:

- Johanna Pohl: Conceptualisation, Methodology, Data curation, Investigation, Formal analysis, Software, Writing - original draft, Writing - review & editing;
- Vivian Frick: Conceptualisation, Data curation, Software, Writing - review & editing;
- Anja Hoefner: Data curation;
- Tilman Santarius: Conceptualisation, Writing - review & editing, Funding acquisition, Project administration, Supervision;
- Matthias Finkbeiner: Writing - review & editing, Supervision.

Results summary:

The publication first explains why and how user decisions and behaviour play a central role in determining the unintended higher-order environmental effects (e.g. induction effects and rebound effects) of ICT applications.

The conceptual framework, *The user perspective in LCA*, then classifies relevant user decisions and behaviour into product parameters (e.g. choice of number and size of products and services), and use parameters (e.g. use intensity or active service life). In addition, sociodemographic information on the user (e.g. housing specifics or age) may also contain relevant information for performing an LCA. For each parameter, equivalent LCA modelling elements are provided in the framework to ensure transferability into LCA modelling practice.

The concept is then applied in a case study that investigates the level of energy savings that need to be achieved by an SHS in order to exceed the environmental effects from producing and operating the SHS. The interdisciplinary study design combines an online survey conducted among smart home users to collect use-related primary data (e.g. composition of the average SHS, changes in heating behaviour and housing specifics), and life cycle assessment. Data collected through the online survey informs life cycle modelling (e.g. definition of product system, definition of functional unit).

According to the online survey, the average SHS consists of nine components (including the smart heating devices), with a total of 25.4 devices. There are no significant changes in heating behaviour compared to the control group. LCA results show that using an SHS with smart heating leads to reductions for the impact categories Climate Change (GWP) and Primary Energy Demand (PED). However, net savings are much smaller than the actual savings in heating energy. For the impact categories Abiotic Depletion Potential (ADP) and Ecotoxicity (Ecotox), no net savings can be achieved. With regard to higher-order effects of ICT application, induction effects play a major role. For the average SHS, no rebound effects were observed.

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Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home?

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ABSTRACT

By improving energy management, smart home applications may reduce household energy consumption. This study therefore examines environmental saving potentials of a smart home system (SHS) with smart heating in Germany from a life cycle perspective. Research on the energy saving potential of an SHS usually focuses on single applications rather than the entire system and hence misses life cycle impacts of the system itself. To overcome this limitation, this study takes an interdisciplinary user-driven approach. We conduct an LCA of an average SHS in Germany that includes smart heating for five heating energy saving scenarios. The components of a representative SHS were determined by an online survey among users of smart homes with smart heating (N = 375) in Germany. As a precondition, net savings can only be achieved when the environmental effects from savings in household heating energy exceed the effects from producing and operating an SHS. The results of our case study for the impact categories Climate Change (GWP), Primary Energy Demand (PED), Abiotic Depletion (ADP) and Ecotoxicity (Ecotox) are heterogeneous: we show that savings of GWP and PED can be achieved by an SHS that includes smart heating. However, minimum savings of 6% of annual heating energy over 3.1 years for PED and over 2.4 years for GWP need to be realised by an SHS in order to exceed the environmental effects caused by their production and operation. For ADP and Ecotox, the smart home represents a further environmental burden. We show that including both the life cycle perspective and user-driven parameters is crucial when determining the total environmental effects of smart homes. Future research should further explore these links between the user perspective and LCA.

1. Introduction

Private households' energy consumption accounts for approximately 25% of total energy consumption throughout the European Union (eurostat, 2018a), and space heating accounts for approximately two thirds of the energy consumed by private households (eurostat, 2018b). The heating sector thus plays a decisive role in reducing total energy consumption and associated greenhouse gas (GHG[1]) emissions.

Smart home technologies are discussed as one potential technical approach to reduce household energy consumption and associated GHG emissions (Floričić, 2020; Hargreaves et al., 2018; Sintov and Schultz, 2017). The term "smart home" is used to describe various networked applications in the home. Various different definitions of the term "smart home" can be found in the literature. We adopt the definitions provided by Gram-Hanssen and Darby (2018) as well as by Strengers und Nicholls (2017), which understand smart homes as homes "in which a communications network links sensors, appliances, controls and other devices to allow for remote monitoring and control by occupants and others" (Gram-Hanssen and Darby, 2018). The purpose of a smart home is to provide frequent services such as energy management, home

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[1] Abbreviations: GHG - Greenhouse gas; SHS - Smart home system; LCA - Life cycle assessment; ICT - Information and communication technology; HEMS - Home energy management system; EoL - End of life; RF - Radio frequency; GWP - Climate Change; PED - Primary Energy Demand; ADP - Abiotic Depletion; Ecotox - Ecotoxicity; FU - Functional unit; PCB - Populated circuit board.

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automation, security or comfort to occupants (Strengers and Nicholls, 2017). The definition does not include requirements for the degree of networking in the household, nor does it include requirements for specific functions and technical standards to be met. As will be shown below, this omission also affects questions relating to the environmental modelling of the system, e.g., choice of product system and system boundaries.

The energy saving potential of a smart home system (SHS) stems from process monitoring and automation (Habibi, 2017; van Dam et al., 2013) by using sensors and intelligent (learning) algorithms. Applications include regulation of room temperature, e.g. by smart thermostats or smart window control; lighting control depending on room occupancy, e.g. by occupancy based lighting or smart lighting; recommendations for energy savings through visual feedback (e.g. home energy monitoring); or optimisation of overall energy consumption through the combination of different smart home technologies in the smart home (IEA 4E, 2018). In contrast to the other functions, the saving potential of smart heating management is considered particularly high (Beucker et al., 2016). There are few studies to date that attempt to quantify energy saving potentials of smart heating: Depending on the technology, heating energy savings are up to 10% for smart thermostats and smart temperature control of specific rooms ('smart zoning'), and up to 20% for smart window control and home energy monitoring (Ford et al., 2017; NEEP, 2015; Urban et al., 2016). In a recent study, the International Energy Agency (2018) provides a detailed overview of different smart home technologies and their corresponding energy saving potential. However, due to the small number of studies and the different modelling approaches, no general conclusions can yet be drawn on the energy saving potentials of these different technologies (IEA 4E, 2018).

For a more accurate depiction of environmental effects of smart home technologies however, it is necessary to not only consider the energy saving potential of specific technologies, but also environmental effects from producing and operating these technologies as well as unintended side effects from their application (Pohl et al., 2019a). The latter effects result from behavioural changes due to efficiency gains (rebound effects) or from increased device purchase (induction effects) (Rattle, 2010; Walnum and Andrae, 2016). In this context, motives for using the smart home also play a role in the overall environmental assessment (Frick and Nguyen, in press). This was also shown in a qualitative interview study (Jensen et al., 2018), which identified differences in the composition of smart home systems depending on the type of usage motive (help/comfort, optimisation, and hedonism).

However, previous research on the environmental effects of an SHS has a rather product-related focus, which either lacks a life cycle perspective or only addresses single applications and, hence, neglects environmental effects of other functions, which are dependent on user behaviour and choices in the smart home composition (van Dam et al., 2013). As a consequence, the importance of SHS in reducing energy demand may be overestimated. One of the reasons considered is the lack of integration of variances in user behaviour in environmental assessment (Geiger et al., 2017; Girod et al., 2011; Polizzi di Sorrentino et al., 2016). However, methodological proposals for a comprehensive environmental assessment of products that also includes effects from the product's application are still pending.

To address these research gaps, we pursue an interdisciplinary approach for a more systematic integration of user decisions and user behaviour into life cycle assessment (LCA). We focus on smart homes that include smart heating because those smart home types have the potential to substantially reduce energy consumption. The study's rationale is to measure environmental effects of average smart home systems that exist in reality. Therefore, we do not only assess the impact of smart heating devices (saving potential), but also include other components that are part of an average SHS (induction effects) as well as reported changes in usage behaviour (rebound effects) to assess the environmental effects of an SHS. We use primary data from a user survey among smart home users in Germany for our composition of the average SHS in Germany and include all respective components into our life cycle modelling.

We address the following research question: What energy savings must a SHS achieve in order to exceed environmental effects caused by producing and using the SHS? This question touches on questions concerning the composition of an average SHS, the environmental relevance of devices that cannot be attributed to smart heating and whether significant differences can be found between single impact categories.

The paper is structured as follows. In Section 2, we describe the state of research on environmental effects of the smart home and identify research gaps in assessing the environmental effects of smart home applications. To address these gaps, we present an interdisciplinary conceptual framework combining LCA and behavioural research that allows us to systematically integrate the user perspective into LCA in Section 3. Building on that, we present our interdisciplinary methodology in Section 4. Details of the results are analysed in Section 5, followed by the discussion of relevant findings in Section 6. We end with concluding remarks in Section 7.

2. State of research

A growing body of research is concerned with energy saving potentials and the environmental effects of smart homes. It includes studies that quantify the energy saving potential of smart home applications on the basis of operational energy demand. For instance, Kersken et al. (2018) compared smart heating control systems and estimated average savings potentials of 8–19% of final energy for heating and hot water, depending on household size and building type and age. In a field study, Rehm et al. (2018) determined an average heating energy reduction of 4% with smart heating control. The study involved 120 households and found a maximum energy reduction of more than 30% by using smart heating devices. At the same time, however, the study found that energy demand increased by more than 25%, an increase said to be due to incorrect handling and monitoring of the system as well as to changes in the heating surface (Rehm et al., 2018). Walzberg et al. (2017) investigated the sustainability potential of smart homes using agent-based modelling. Results showed a reduction potential of smart energy feedback information displayed to users of up to 2% for electricity consumption, climate change and further impact factors. When potential rebound effects are also considered, reduction potential can be lowered by up to 24%, leading to a maximum reduction of 1.5% of overall electricity demand (Walzberg et al., 2017). However, these studies have been criticised for taking into account only the operational phase (van Dam et al., 2013). Since environmental effects along the life cycle of the SHS are not considered, those studies give an incomplete picture of the associated environmental impact.

Several studies have investigated energy saving potentials of smart home technologies from a life cycle perspective. Castorani et al. (2018) investigated the environmental effects of introducing smart kitchen hoods. The results show that smart kitchen hoods have similar energy savings and GHG reduction potentials as manually operated kitchen hoods. However, sensors and Information and communication technology (ICT) equipment of the smart kitchen hood lead to increases in metal depletion and human toxicity (Castorani et al., 2018). van Dam et al. (2013) analysed three different home energy management systems (HEMS; energy monitor, energy management device, complex energy management system). The results show that the cumulative energy demand of HEMS differ by a factor of up to 10 while energy payback times are between 6 and 18 months, depending on the device and energy saving scenario (van Dam et al., 2013). In contrast, Beucker et al. (2016) computed low payback times for energy and GHG emissions from energy management systems in residential buildings with central heating and potential energy savings of 20% per year. Louis and Pongrácz (2017) investigated environmental effects of implementing HEMS as a function of the level of automation and number of inhabitants. Their results showed that the smart home application contributed to decreasing energy demand (level of automation: smart metering, two or more inhabitants) or increasing energy demand (level of automation: energy management system with/without automation, irrespective of number of inhabitants) (Louis and Pongrácz, 2017).

Even the life cycle studies presented above only provide an incomplete picture of environmental effects of smart applications because the calculated energy savings mostly apply to single applications (e.g., smart heating) (van Dam et al., 2013). Other functions, in particular those that do not contribute to potential energy savings as well as variations in user behaviour or possible counteracting effects such as rebound effects, have barely been investigated (Ford et al., 2017; Pohl et al., 2019a; van den Brom et al., 2018). Overall, this omission may lead to the importance of smart home systems in reducing energy demand being overestimated.

3. Framework

In this paper, we apply the framework of environmental effects of ICT initially presented by Berkhout and Hertin (2001) and further developed by Hilty and Aebischer (2015) and Pohl et al. (2019a) to the case of smart homes. A central finding of the framework was that, in addition to the life cycle effects of the devices, effects from application and resulting changes in user behaviour are also decisive for the environmental impact of ICT. Based on this framework, we develop a specific LCA methodology that incorporates the relevance of user behaviour and user decisions and their impact on LCA modelling. In the following, the conceptual approaches regarding the environmental effects of smart homes and their assessment as part of an LCA will be introduced.

3.1. *Environmental effects of smart homes*

The framework of environmental effects of ICT (Pohl et al., 2019a) describes first-order environmental effects along the ICT product life cycle due to raw material demand, production, use and disposal and higher-order environmental effects due to application on micro and macro levels. The latter effects can be positive (e.g., through optimisation and substitution of processes) or negative (e.g., through rebound effects and induction effects). Both rebound and induction effects can result from behavioural changes due to efficiency gains (rebound effects) or from an increased choice of options (induction effects) (Rattle, 2010; Walnum and Andrae, 2016).

The framework of environmental effects of ICT can also be applied to smart homes. First-order effects of an SHS describe the environmental effects related to production, system operation and disposal of devices and ICT infrastructure (communication network and data centres). Higher-order effects describe intended and unintended environmental effects of applying the SHS. From an environmental perspective, the intended function is optimisation/management and control of the energy system with the overall goal of saving energy at a household level. Unintended effects may stem from applying and using additional smart home services (i.e., comfort, security) that do not contribute to reducing resource use (induction effect) or from behavioural changes such as increases in heating frequency and heating intensity in the (smart) home (rebound effect). We endeavour to include these user-related effects in addition to the product perspective for a more comprehensive environmental assessment.

3.2. *Integrating the user perspective in life cycle assessment*

It follows from the above framework that user decisions and user behaviour can play an important role when assessing the environmental performance of products. We describe the inclusion of user decision and behaviour in LCA as user perspective in LCA. Those user decisions and behaviour form one aspect considered here under the broader term of "user-driven parameters in LCA", which can be divided into *product parameters* and *use parameters* (see Fig. 1). The concept is based on the approach by Pohl et al. (2019b). 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. For instance, users may purchase an SHS that includes other devices in addition to smart heating. Including such information in the LCA would allow induction effects to be accounted for. Furthermore, there is a direct link from a user's choice of products and services to the *technology parameters* of specific products. These parameters are producer-driven, not user-driven, and include specifications on eco-design principles, the device's energy efficiency, sourcing of raw material and technical service life.

Use parameters focus on use behaviour and include use frequency

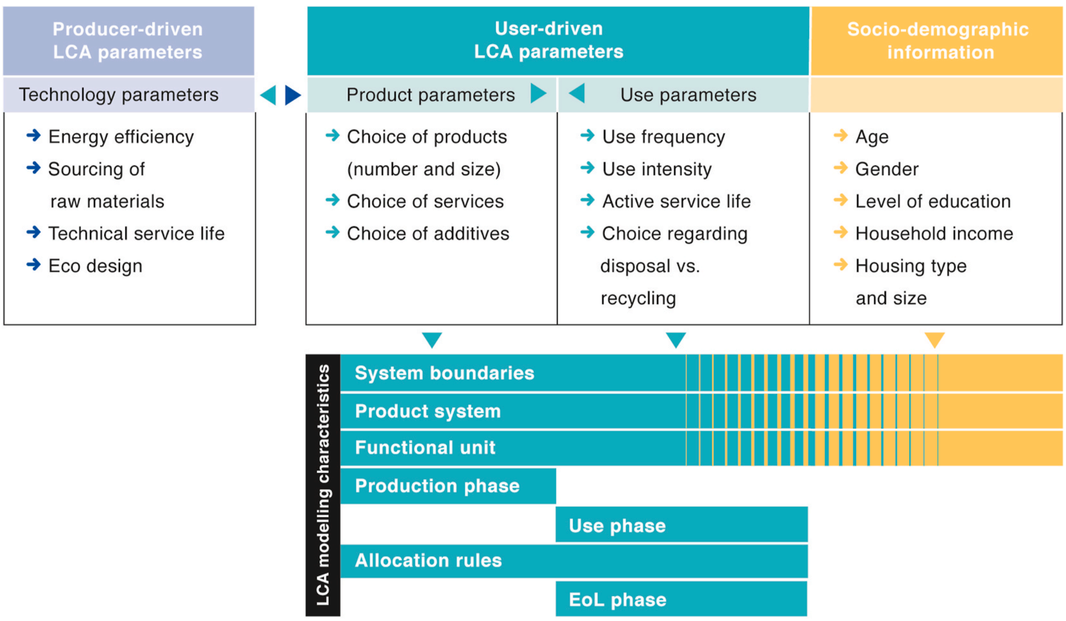

Fig. 1. The user perspective in LCA and its effect on LCA modelling characteristics (own work, adapted from Pohl et al., 2019b).

and intensity, active service life and specific choices regarding End of Life (EoL) scenarios. For instance, users may enjoy higher room temperatures or may heat more rooms than before as a result of their SHS. Including such information in the LCA would allow rebound effects to be accounted for. Users may also decide on specific EoL scenarios, i.e., whether products are disposed of and properly recycled or thrown into residual waste.

Socio-demographic information on the users (e.g., gender, income, education, housing) is also relevant when considering the user perspective in the LCA. For instance, information regarding the housing situation helps specify the functional unit (FU) or may be useful for interpreting the results. In summary, integrating the user perspective into LCA affects, in particular, the goal and scope phase. In addition, information regarding product and technology parameters may also have an influence on the production phase. Product and use parameters may affect use phase modelling. Technology and use parameters may affect the EoL phase. Helpful tools for including the user perspective into environmental modelling can be empirical methods from behavioural or social sciences, e.g., surveys, interviews or Living Labs (Pohl et al., 2019b; Polizzi di Sorrentino et al., 2016; Suski et al., 2020).

4. Methodology and operationalisation

As outlined above, the aim of the case study was to determine the size of energy savings that must be realised by an SHS in order to exceed the environmental effects caused by its production/operation and by unintended or intended side effects (e.g., induction effects). To estimate these minimum requirements for the energy savings of an SHS, an LCA of a typical smart home system in Germany was performed. Composition of the SHS and operationalisation of user-driven parameters in the smart home were based on an online survey among smart home users in Germany. Fig. 2 provides a flowchart depicting our research methodology. In the following, we first describe briefly the methodology underlying the online survey and which of the user-driven parameters were operationalised, before describing our LCA and the approach for calculating the minimum saving effects of an SHS.

4.1. Online survey

The purpose of the online survey was to obtain information about (i) the average housing situation of smart home users in Germany, (ii) the average composition of an SHS that includes smart heating in Germany, and (iii) self-reported changes in heating behaviour after introducing an SHS.

Survey sample An independent institute for data collection for market and social research (norstat) recruited the smart home group and the control group. In the smart home group, $N = 8151$ individuals were screened as to whether their household had a smart heating system, of which initially $N = 644$ participants (7.9%) completed the questionnaire. Of the initial respondents, 269 were excluded due to inconsistent answering, resulting in a final sample of $N = 375$ (4.6%). The control group consisted of an initial sample of $N = 511$ with no screening, out of which 112 were excluded for various reasons, resulting in a final sample of $N = 399$.

Survey procedure The questionnaire for smart home users started with the mentioned screening question for smart heating systems ("Do you have a smart heating system?"). This screening was followed by assessing the number of smart home devices. This was measured stepwise as follows: First, the participants were asked whether they owned electronic device types; second, a filter question assessed how many of each device type they owned and; third, how many of the devices were connected to the smart home. All of the devices that were indicated as connected to the smart home were counted as part of the SHS. Single-choice items assessed how the smart devices were connected (e.g., cable, radio frequency (RF)) and how the users controlled their smart homes (e.g., smartphone, voice control). Then, household data (e.g., living space, source of heating energy) was acquired. Next, we measured heating behaviour during the heating season: First, filter questions assessed whether participants apply different heating temperatures to bedrooms and living areas, as well as during daytime and night-time. Next, participants could indicate the heating temperature, depending on their indication (during daytime and night-time, in bedrooms and living areas). Finally, sociodemographic information, including the living situation, was collected. In the control group, the same questionnaire was completed, with a few differences. An overview of the control and sample group is given in Table 1.

4.2. Operationalisation of user-driven parameters in LCA

We now explain how primary data from the online survey was fed into the LCA and which of the user-driven parameters introduced in the section above (see also Fig. 1) were addressed and operationalised in the study. Operationalisation of the user perspective in our LCA and information on the primary and secondary data sources are summarised in Table 2. Use parameters as well as parts of product parameters were derived from primary data assessed in the online survey: Changes in heating intensity and heating frequency of the smart home (use parameters) were modelled in LCA as expenditure during use phase. Average number and coverage of smart heating devices and other smart home components (product parameters) form the smart home product system. Furthermore, the definition of the FU was specified by information on the living conditions of the average smart home user. For the device performance (technology parameters), as well as for the energy saving scenarios (product parameter) information was obtained from secondary data (e.g., data sheets and other technical documentation provided by a major smart home supplier in Germany).

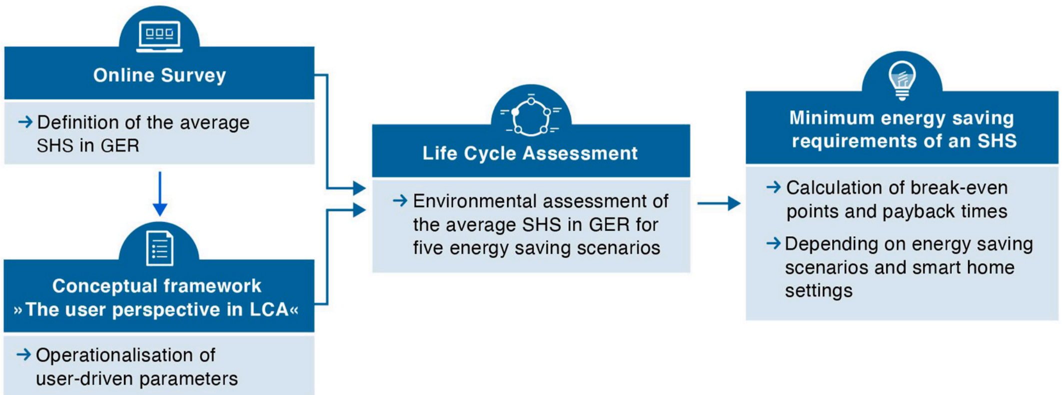

Fig. 2. Research methodology.

Table 1
Sample and control group.

	Smart home with smart heating system	Control group
	$N = 375$	$N = 399$
Individual level		
Age *M* (*SD*)	47.99 (13.2)	52.8 (17.5)
Gender	29.1% female 70.6% male 0.3% other	48.6% female 51.4% male
Household level		
Household income (Median)	3000–3500 €	2000–2500 €
Persons in the household (SD)	2.78 (1.2)	2.3 (1.32)
Square meters (Median)	100–120 m^2	80–100 m^2
House type	61.6% 1–2 family home 37,9% apartment in a building with 3 or more apartments 0.5% other	42.3% 1–2 family home 57.6% apartment in a building with 3 or more apartments 2.8% other
Heating energy source	11.0% electricity 58.9% gas 19.2% oil 3.8% solid fuel (e.g., wood, coal) 7.1% other	13.0% electricity 54.9% gas 24.3% oil 3.5% solid fuel (e.g., wood, coal) 7.3% other

4.3. Life cycle assessment of an average smart home system

For Germany, the average environmental effects of an SHS that includes smart heating is determined by conducting an LCA following ISO 14040 (2006).

Aim and scope The goal of the LCA was to assess minimum saving effects that need to be realised by the average SHS in order to exceed the environmental effects caused by its production and operation. Except for production, the scope of the study is Germany. Country-specific data on the German energy grid mix (reference year 2016) was used. Final assembly was assumed to take place in Germany. Sourcing of the components was assumed to take place worldwide, except for the device housing, which was manufactured in Germany. Our study took into account production phase and use phase. This limitation was justified because a large number of LCA studies on ICT devices and applications show that, in particular, the production phase and use phase are decisive, while the environmental effects due to transportation and EoL are negligible (Castorani et al., 2018; Louis and Pongrácz, 2017; Teehan and Kandlikar, 2012). Only the operational phase was considered for the ICT infrastructure because, for GHG emissions and electricity demand, effects from producing the ICT infrastructure are negligible (Malmodin et al., 2014). In addition, little data is available for the energy demand of an ICT infrastructure over and above that of the operational energy, and what is available is inconsistent.

A proxy device was defined that represented the components of the SHS based on weight. The FU was defined based on a proposal by Suski et al. (2020), who suggest expanding the FU to household level in order to include all types of user-driven parameters into the LCA. Using the living conditions of the average smart home user from our online survey, the FU was defined as “110 m^2 apartment space in Germany managed (monitored and controlled) for 5 years”. The product system was defined as a “typical SHS that encompasses heating in Germany”. The system boundaries of the SHS used on average include the SHS devices and the ICT infrastructure (see Fig. 3).

The different components that comprise the average SHS based on our survey are described in detail in the results section below. Since there is no standard regarding the functions that constitute an SHS, we followed the typology of usage motives by Jensen et al. (2018) and accordingly included smart home devices in the product system that provide the functions energy management, security, home automation or comfort. All other devices used to access the system for monitoring and control are outside the system boundaries, as they are primarily used for other purposes. Outside the scope were also all appliances related to heating, such as boilers and radiators. In line with IEA 4E (2019), the life time of the devices was set to 5 years.

Sensitivity analysis was used to assess the relevance of changes in operational energy demand, of changes in energy grid mix and of changes in the system’s active service life. Fig. 4 provides an overview displaying impact categories, different SHS settings and five energy savings scenarios that were analysed.

Inventory Analysis GaBi LCA software was used for inventory analysis and impact assessment. If available, inventory data was taken from the GaBi database Service Pack 39, except for *electric connector, printed wiring board*, and *heat production from hard coal briquette stove*, where inventory data was taken from the ecoinvent 3.5 database. The different components of the average SHS were included proportional to average coverage among the smart home users and number of devices per component, based on the online survey. Related technical data (weight, load) was derived from product data sheets of major German smart home suppliers and from reports of the International Energy Agency. In supplementary material A we display detailed information on technical data and references. Average coverage and number of components/devices of the SHS are described in the results section below.

Together with a major supplier of smart home devices, control unit “X1” was selected as a weight-based proxy device representing the composition/production phase of all components of the SHS. The

Table 2
Operationalisation of the user perspective in LCA in the smart home case study.

Parameter in LCA	Operationalisation in LCA	Data sources	Environmental effects
Primary data from online survey			
Use Parameters	Proportionate increase/reduction of average annual heating energy demand due to changes in heating behaviour; included as expenditure of the system	Changes in heating temperature and day/night frequency of rooms heated of smart home group compared to control group	Rebound effects
Product parameters	Definition of the smart home product system	Number and coverage of smart heating devices and smart home infrastructure	First-order effects
		Number and coverage of other smart home components	Induction effects
Socio-demographic information	Specification of the functional unit	Information on the average housing size	.
Secondary data from literature			
Product parameters	Heating energy savings from the application of smart heating devices; included as savings of the system	Definition of energy saving scenarios from the application of smart heating according to Beucker et al. (2016), Rehm et al. (2018), Urban et al. (2016)	Optimisation effects
Technology parameters	Inventory data	Technical files exemplarily from one of the main producers in Germany, desktop research regarding load and sourcing of raw materials of devices	First-order effects

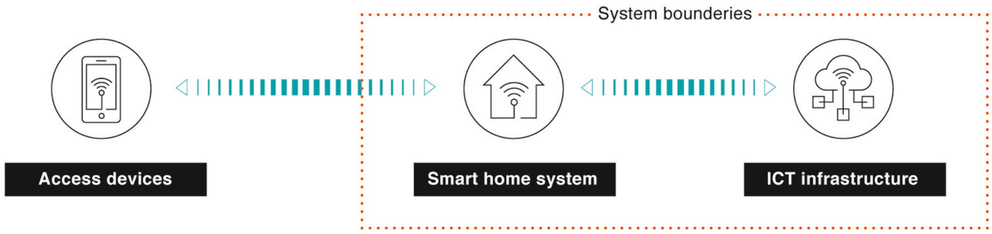

Fig. 3. System boundaries of the SHS.

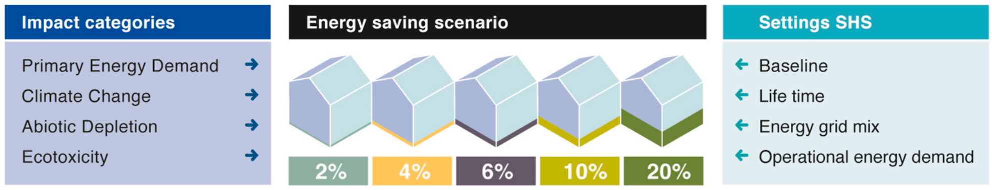

Fig. 4. Overview of impact categories, energy saving scenarios, and SHS settings considered in the study.

reasons for this simplification were twofold. First, based on the case study design, it was not possible to assign the average SHS to a specific supplier. A simplification therefore had to be made. Second, collecting inventory data for ICT devices is challenging (Moberg et al., 2014; van Capelleveen et al., 2018). Due to the proportionately high weight of the populated circuit board (PCB) in the device, it can be assumed that the inclusion of effects from production is slightly above average. This device was consciously chosen to ensure that the environmental effects from its production were fully covered. The proxy device was disassembled and weighed/measured. In line with other studies, the printed wiring board for a laptop mainboard was selected as the PCB.

The energy use model for downstream energy use was energy use per device (IEA 4E, 2019). We assumed that all devices ran under full load. This assumption was necessary due to a lack of data regarding average standby times of smart home devices. For calculations, the German grid mix was assumed. Upstream energy was required for transmitting data over the Internet and processing data in data centres. Here, the energy use model was energy intensity (IEA 4E, 2019), and data transmission in kWh/GB was calculated for home and access network, core and edge network and data centre, in line with the work by Schien and Preist (2014). For upstream energy, the EU-28 grid mix was assumed. Currently, no information is available on the average amount of data transmitted per year by smart home devices. Therefore, the average global IP traffic per year by Internet-of-Things devices (Barnett et al., 2018) was used here.

Heating energy saved due to the smart home's optimisation effect was included in the assessment as savings. Five heating energy saving scenarios (2%, 4%, 6%, 10%, and 20% of annual heating energy demand) were applied to the average heating energy consumption of German households, based on the average apartment size, apartment type and heating energy source according to the online survey (see also Table 1) and energy consumption statistics of German households (co2online, 2019). For each heating energy source, reference heating appliances of households were defined in line with Tebert et al. (2016). The inclusion of specific heating appliances is necessary in order to take into account the appliances' different degrees of efficiency per unit of thermal energy provided. In supplementary material B we provide modelling details.

Impact Assessment The results are presented for the impact categories Climate Change (ReCiPe 2016 v1.1 (H)), Primary Energy Demand (from renewable and non-renewable resources), Abiotic Depletion (CML2001 - Jan. 2016, elements) and Ecotoxicity (USEtox 2.1, recommended). The indicators Climate Change (GWP) and Primary Energy Demand (PED) were chosen to analyse the optimisation effects related to the energy savings and GHG savings of the SHS from a life cycle perspective. The indicator Abiotic Depletion (ADP) was chosen to provide an insight into the mineral material present in the smart home. Ecotoxicity (Ecotox) is a measure for assessing the toxicity of all emissions from the technosphere to air, water and soil and is also used to analyse the ratio of optimisation effects and first-order effects from producing and operating the devices. We carefully chose the impact categories to address different environmental impacts and to investigate potential burden shifting through implementing SHS.

4.4. *Calculation of net saving effects*

Net saving effects of an SHS can only be observed when the energy saved by having smart heating (optimisation effect) exceeds the effects that contribute to increasing resource consumption (through producing and operating the system as well as through changing consumption patterns).

The break-even point E_{BE}, when environmental effects from energy saved E_{Saved} equal environmental effects that stem from production $E_{Production}$ and operation $E_{Operation}$ and changes in behaviour $E_{Behaviour}$ can be described as follows:

$$E_{BE}(t) = E_{saved}(t) = E_{Production} + (E_{Operation} + E_{Behaviour})\cdot t$$

Except for effects from production, all other effects are time-dependent. The equation, when resolved to t, gives payback time t_P, which describes the point in time at which the effects from production and operation/behaviour change have been amortised within a particular savings scenario:

$$t_P = \frac{E_{Production}}{E_{saved} - E_{Operation} - E_{Behaviour}}$$

Since information about the actual optimisation potential of the SHS cannot be measured directly through the survey method, we follow the approach of van Dam et al. (2013) and define energy savings scenarios for the smart heating device. We draw on results from previous studies by Beucker et al. (2016), Rehm et al. (2018) and Urban et al. (2016) and assume five energy saving scenarios of 2%, 4%, 6%, 10% and 20% of annual heating energy demand to determine under which conditions in which scenarios the break-even point is reached.

5. Results

First in this section, we present how, using the results of the online survey, we defined the SHS. Second, we present results from our LCA and discuss net saving effects of the SHS for five saving scenarios.

5.1. Description of the smart home system and relevant user behaviour

The results of the online survey provide information on the composition of the SHS as well as information on changes in heating behaviour in the smart home. In Fig. 5, the average smart home based on the online survey is displayed. The average SHS consists of components that provide services in the smart home and of components that can be assigned to smart home infrastructure. Based on the survey, only those networked components actually interconnected to each other were included in the definition of the smart home product system. In addition to smart heating related components (here: room and radiator thermostats), the average SHS was found to consist of eight additional components, which provide various services, plus the control unit, which functions as the interface between the SHS and the Internet. A total of 25.4 devices were identified (with a coverage between 30% and 100% among all smart home users) with different components present several times in the system. The smart home devices exchanged and received information via a communication network. Based on the survey, WiFi is the most commonly used RF standard.

In order to determine the extent of rebound effects, we further analysed changes in heating behaviour of the smart home sample and the control group. An average room temperature of 19.43 °C was determined for the smart home sample and 19.45 °C for the control group. Since the differences between the smart home group and the control group are not significant, no rebound effect could be determined and the annual heating energy demand thus remained unchanged. Further information on the average SHS and relevant user behaviour based on the survey can be found in the supplementary material A.

5.2. Environmental effects of the smart home system

First, environmental effects through production, operation and network transmission (first-order effects) were analysed over the life time of 5 years for the different impact categories (see Fig. 6).

The ratios of the different origins vary for GWP, PED, ADP and Ecotox. While for impact categories GWP and PED, the environmental effects due to the system's operational energy demand are dominant (62%, 65% resp.), ADP originates almost solely (99.7%) from production and material input. For Ecotox, environmental effects from production and material input are dominant (68%). Environmental effects of data transmission are insignificant for all impact categories due to the low data volumes.

Within the SHS, the environmental effects of the smart heating component is largest for all four impact categories. The reason for this is that the smart heating component accounts for the largest weight share and highest operational energy demand in the overall SHS. The environmental effects of the control unit are the second largest for GWP and PED due to the component's high operational energy demand. For ADP and Ecotox, the security camera component is the second highest in the SHS due to the high self-weight of the component. Overall, components that do not have an essential energy optimisation function account for 79% of GWP, 80% of PED, 62% of ADP and 70% of Ecotox in the SHS.

In the next stage of this study, we investigated different savings scenarios. Below, we present the results of that stage (see Fig. 7 for GWP; corresponding figures for PED, ADP and Ecotox can be found in supplementary material C).

For GWP and PED for the saving scenarios 2% and 4%, environmental effects of the SHS due to production and operation are greater than the environmental effects due to smart heating; operating the system over 5 years increases GWP and PED. For the saving scenarios 6%, 10% and 20% the environmental effects of the system due to production and operation are smaller than the environmental effects due to smart heating; operating the system over 5 years reduces GWP and PED and net savings can be achieved. For ADP and Ecotox, however, environmental effects from producing and operating the system over 5 years are greater than the effects from heating optimisation.

Sensitivity analyses showed that changes in (i) operational energy demand, (ii) in the energy grid mix and (iii) in the duration of the system's service life have particularly an effect for GWP and PED. For ADP and Ecotox, changes are marginal and do not affect the overall results.

Lowering the system's operational energy demand changes the results for GWP and PED. For those impact categories, saving effects in the 4% scenario are already larger than those from production and operation, and therefore, net savings can be achieved.

Powering the SHS with green energy significantly lowers GWP of operational energy demand but leads to increases in the other impact categories. For GWP, net savings can be achieved in the 2% scenario. For PED, ADP and Ecotox, the switch to green energy has no effect on the overall results. The effect of applying the Future 2030 Grid Mix Scenario is particularly evident for GWP and PED for the 4% and the 6%

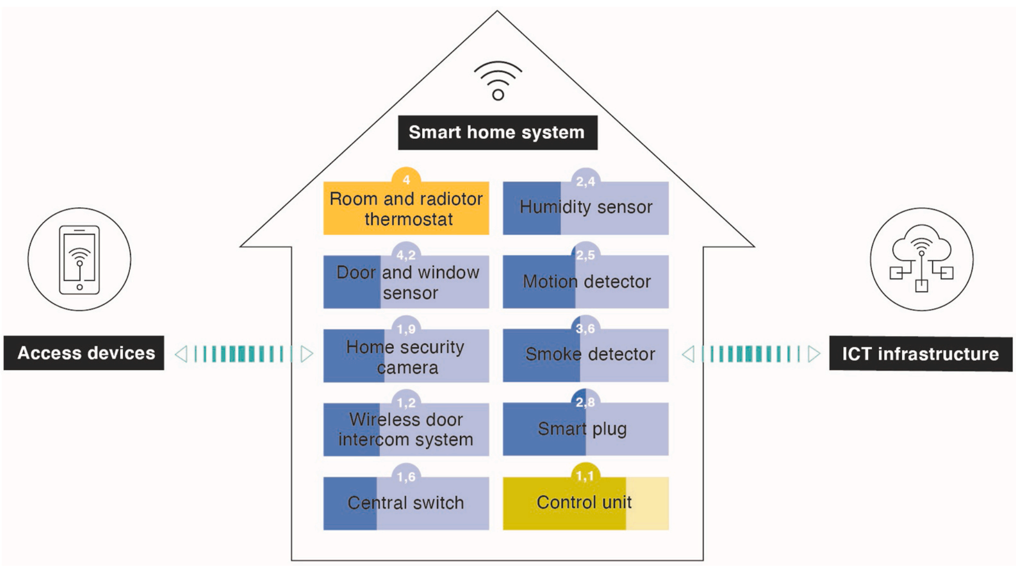

Fig. 5. The average SHS that encompasses heating in Germany. The numbers within the circles display the number of devices per component. The colour-coded boxes display the average coverage of the component among all smart home users.

Fig. 6. Relative share of GWP, PED, ADP and Ecotox of the SHS for production, operation and data transmission over life time.

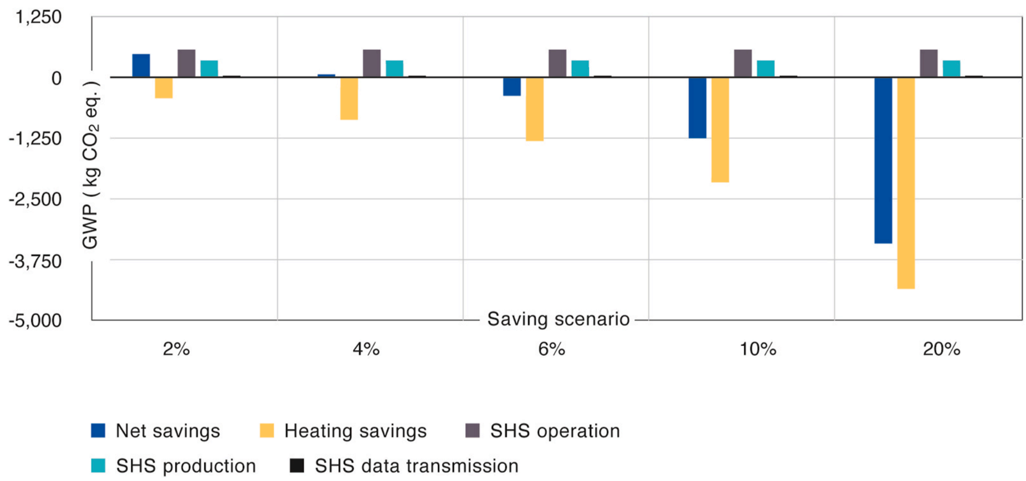

Fig. 7. Changes in impact category Climate Change (GWP) of the SHS for 5 scenarios and a life time of 5 years. The negative values are savings in the overall system.

scenarios. For GWP, optimisation in the 4% scenario are already greater than those effects from production and operation. For PED, amortising first-order effects from production and operation requires at least a 6% scenario. However, compared to the baseline, the saving effects are up to 10% larger.

Doubling the active service life to 10 years halves the allocated share of environmental burden from material input and production per year and doubles actual heating energy savings. For GWP and PED, saving effects can be achieved in the 4% scenario and above. In supplementary material C we provide detailed results.

5.3. Net saving effects of the system

The study shows that the use of an SHS can indeed contribute to savings of GWP and PED. However, actual net savings are much smaller than the savings in heating energy. This is due to the environmental effects from producing and operating the SHS, which have to be subtracted from the heating energy savings. Considerable differences in the amount of net savings over 5 years and payback times can be observed for the different saving scenarios across the impact categories. For GWP, net savings over time and payback times t_P are illustrated in Fig. 8 for the five energy saving scenarios. Detailed results for all the impact categories are compiled in the supplementary material C. For GWP and PED, net savings over the lifetime of 5 years can be seen for the 6%, 10%, and 20% savings scenarios. For GWP, net savings are between 381 kg CO_2 eq. for the 6% scenario and 3423 kg CO_2 eq. for the 20% scenario. For PED, net savings range between 3533 MJ for the 6% scenario and 51,228 MJ for the 20% scenario. For GWP, payback time t_P is between 6 months and 2.4 years depending on the scenario. This means that the SHS must be operated for up to 2.4 years with minimum savings of 6% of annual heating demand in order to outweigh the environmental effects from producing and operating the SHS. Only then can net savings be realised. For PED, payback time t_P is between 6 months and 3.1 years depending on the scenario. Corresponding break-even points for GWP and PED differ widely for the saving scenarios. This is due to payback time and thus operational energy demand decreasing with increasing savings level. For ADP and Ecotox, no net savings are achieved; first-order effects are considerably higher than the savings achieved through smart heating. For Ecotox, however, the payback time for the 20% scenario is 5.4 years and thus slightly longer than the assumed service life of five years. However, due to the underlying uncertainty of the impact category Ecotox (Rosenbaum et al., 2008), no significant

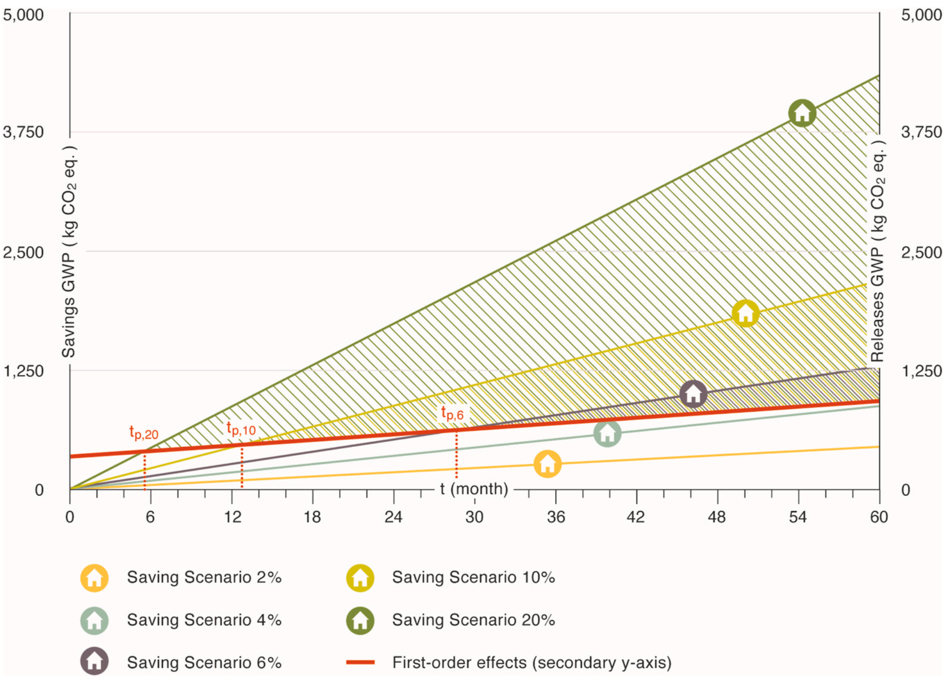

Fig. 8. Gross and net savings over time for the five energy saving scenarios for GWP. Primary y-axis represents SHS savings, secondary y-axis represents SHS releases. The marked area above '*First-order effects*' represents the net savings in each scenario. For 2% and 4% scenario, no net savings are achieved.

benefits can be determined here. As part of our sensitivity analyses, we also calculated the payback times for changed SHS settings (changes in operational energy demand and changes in the energy grid mix). The results are compiled in the supplementary material C.

6. Discussion

In the following, we discuss the results concerning methodological considerations and limitations and identify future research needs. We further derive implications for practitioners and policy.

6.1. The user perspective in LCA

With the present study, we have proposed a methodological approach that allows for a more systematic integration of user decisions and user behaviour into LCA. By including user-driven parameters in our environmental assessment, we did not focus only on one part of SHS (i.e., the smart heating component) but on the average SHS in the context of its application. This focus is important in order to provide a complete picture of environmental effects of SHS and related net saving effects. As the user-driven parameters are mirrored in the framework of environmental effects of ICT, our approach can also be used to assess user-related higher-order effects of ICT (i.e., rebound and induction effects).

The importance of the user perspective for the overall result manifests in our study at a number of points. First, the shift from the product perspective to the user perspective is reflected in the definition of the FU. The FU is not limited to one product but refers to the application of the entire SHS in relation to the basic heating energy unit (apartment size) of the average smart home user. The definition of the FU thus proves to be crucial in determining the perspective. Second, we found that the product system consists of a total 25.4 devices that can be assigned to eight components and the control unit, in addition to the smart heating component (product parameters). The components that provide other services than energy optimisation account for more than 60% of GWP, PED, ADP and Ecotox from producing and operating the SHS. Without the inclusion of these components, the calculation for break-even points would have been significantly lower for all scenarios, thus overestimating net saving effects. This also becomes evident when comparing our results with other studies. van Dam et al. (2013) calculate energy payback times for energy management devices between 6 months for a 10% saving scenario and 18 months for a 2% saving scenario. Beucker et al. (2016) calculate a payback time of less than one month for energy and GHG emissions for a 20% energy saving scenario of energy management systems in residential buildings with central heating. In both studies, calculated payback times are lower than in our study. One of the reasons for this discrepancy is the definition of the product system in said studies, which only includes single applications and not the entire SHS. Third, our approach also provided for integrating changes in heating intensity and heating frequency into the modelling (use parameters). However, since we did not find any significant changes in heating energy and intensity in the smart home sample, this parameter remained unchanged. We have shown that integrating the user perspective into LCA can affect all phases of the LCA, from defining the goal and scope of the study to collecting inventory data and interpreting results. Contrary to the obvious assumption that including user behaviour is mainly relevant in the use phase, it is mainly those aspects related to defining goal and scope that decisively determine the perspective. So far, however, there is still a lack of underlying interdisciplinary concepts that address the user perspective in a profound way in LCA. Initial work has been presented by Polizzi di Sorrentino et al. (2016) and by Suski et al. (2020), and the study in hand should also be understood in this sense. However, more interdisciplinary research is needed to better understand the role of user behaviour and related environmental effects as well as the interplay of behavioural concepts such as acquisition motivation, user motivation or pro-environmental behaviour within environmental assessment. To ensure comparability of results in LCA that include the user perspective, there is a need to develop recommendations for the definition of FU, product system and system boundaries. This development is particularly relevant with regard to addressing multifunctionality. Initial considerations have been made in investigating product/service-systems in LCA (Kjaer et al., 2018), but adopting these approaches to user perspective in LCA is still pending.

6.2. Strength and limitations

This LCA has some limitations and assumptions. The LCA was modelled cradle-to-use, excluding the transportation and EoL phases. A full life cycle perspective should include all phases, cradle-to-grave, into the modelling. Including the transportation phase may increase the total environmental effects of an SHS. Depending on the actual EoL scenario (e.g,. incineration, recycling), credits for the different impact categories can be expected, and the SHS total environmental effects may slightly decrease. However, as we had no information about user-driven EoL choices, they could not be included in the study. Further investigations are needed into user-related practices of different EoL scenarios of electronic devices, such as that presented by Frick et al. (2019). For ICT infrastructure, only the operational phase was considered. Including the production phase of the ICT infrastructure would probably lead to interesting results for impact categories such as ADP.

In line with other studies, the service life of the SHS was set to 5 years, and sensitivity analysis was used to determine the environmental relevance of doubling the service life to 10 years. Results showed that prolonging the system's service life is environmentally beneficial, in particular for settings with low energy optimisation. The results of this study, however, only apply to life times of 5 years and 10 years. Prolonging or shortening a system's service life (even of some components of the system) beyond this period was not examined.

The use of a proxy device representing all smart home components is also a simplification. A simplification was necessary as it was not possible to assign an average SHS to a specific supplier. The results could thus be subject to variability. However, this is a common problem when modelling electronic devices. Like others (Moberg et al., 2014; van Capelleveen et al., 2018), we were confronted with the complex collection of inventory data for ICT devices. One solution to this complexity is to apply simplified approaches. Thus, together with a major smart home supplier, we selected a proxy device representing all smart home components. The device was used as a weight-based proxy for all devices of the SHS. The modelling of the proxy device was based on production data from the major smart home supplier. Nevertheless, a simplification in inventory data selection was still needed and the ecoinvent data set "*printed wiring board, mounted mainboard, laptop computer, Pb free*" was used for PCB. Comparison with other modelling approaches for PCB shows a rather conservative modelling, and the environmental effects from the production phase of the SHS might be overestimated. However, running the assessment with variations of 90% and 110% of environmental burden from the production phase showed that variation in the overall results was not significant. Payback times for PED, GWP, ADP and Ecotox changed slightly, but general conclusions regarding the achievement of net savings within the specific saving scenarios did not change. Overall, this study showed, once more, the strong need for more product-specific inventory data for electronic devices, in particular for global data sets for mixed electronic devices.

Further assumptions and simplifications in terms of the definition of the product system and heating behaviour scenarios were made. Based on participants' self-report of owned devices we modelled the average SHS. We chose self-report surveys as a means to provide detailed information about which smart home compositions exist in practice. Yet this method also has its limitation, as self-reports are sometimes subject to memory bias or limitations of knowledge. Thus, measurement errors may occur, e.g. with regards to heating temperature or number and type of networked devices in the smart home. To counteract this, personal in-home surveys or semi-structured interviews could be conducted instead of online surveys. Furthermore, information about the actual optimisation potential of the SHS cannot be measured directly through the survey method. We therefore defined energy saving scenarios based on existing studies, which may differ from the actual savings potentials of smart home technologies as described by IEA (2018). To validate our energy saving scenarios, future studies should conduct long-term measurements of energy consumption in households, e.g., by observing targeted households in a Living Lab study. They may further examine what share of energy savings can actually be attributed to the SHS and where external conditions such as building refurbishments are the cause.

By comparing the effects for changing the average electricity grid mix to 100% Green Energy/Future 2030 Grid Mix (Sensitivity Analysis), green energy was counted double. This issue can be avoided by offsetting the share of renewable energy in the average electricity grid mix.

6.3. Implications for practitioners and policy

According to the study, achieving net saving effects is tied to preconditions. It was shown that the levels of net saving effects for GWP and PED depend on three factors: (i) the environmental effects from producing the devices, (ii) the level of operational energy demand, and (iii) the level of actual energy savings. Hence, the smart home devices should be designed to last as long as possible. However, there are cases where active service life of smart devices is shortened due to incompatibilities with software requirements (software-induced obsolescence of hardware). This obsolescence could be prevented by using open source standards and by guaranteeing a right to repair. Standby settings and applying low-energy communication standards significantly lower the level of the system's operational energy demand. The level of actual energy savings depends greatly on the overall technological design approach (Beucker et al., 2016). A standard defining what a smart home actually is and determining the overall technical design would ensure maximum saving effects for all smart home applications.

If a minimum 6% of annual heating energy can be saved by smart heating devices, then, as we have shown, the use of an SHS can contribute to overall GWP and PED savings. Applied to the different smart home technologies such as smart thermostat, smart window control or home energy monitoring (IEA 4E, 2018), this means that the level of savings can be achieved by almost all currently available smart heating devices. In this regard, there are only limitations for smart thermostats, for which saving effects can also be less than 6% of annual heating energy demand. However, at the same time, the optimisation of heating energy demand and substitution of parts of the heating energy with electricity leads to impact shifting (here, GWP and PED decrease, while ADP and Ecotox increase). Whether these impact shifts are appropriate is not least a societal negotiation process.

7. Conclusions

The case study examined the environmental saving potentials of an average SHS with smart heating in Germany from a life cycle perspective. To estimate minimum requirements for the energy savings of an SHS with smart heating, we applied an interdisciplinary user-centred approach that also includes environmental effects from the application of smart heating into life cycle modelling. To define what an average smart home looks like and to estimate variances in user behaviour, we used primary data from a user survey among smart home users in Germany. Our case study showed that the average smart home with smart heating consisted of eight additional components with a total of 25.4 devices. Furthermore the case study showed that environmental savings can be achieved by SHS when they include smart heating. However, net savings are much smaller than the actual savings in heating energy. Minimum savings of 6% of annual heating energy over 3.1 years for PED and over 2.4 years for GWP need to be realised by the SHS in order to exceed the environmental effects caused by producing and using the SHS. For ADP and Ecotox, no net savings can be achieved and the smart home represents a further environmental burden. The case study thus further shows that there are significant differences between single impact categories and that the implementation of SHS comes along with potential burden shifting. Through the interdisciplinary study design developed here, which emphasises the user perspective, fundamental criticisms of previous study designs, i.e., lack of life cycle perspective, focus on single applications only, lack of user-related effects, could be overcome. The interdisciplinary LCA methodology "The user perspective in LCA" further contributes to the methodological investigation of the environmental effects of ICT application.

The holistic focus applied here is key to identifying realistic opportunities to improve environmental performances and to provide conscientious advice to political decision-makers, businesses and the consumers. Three key conclusions for future research can be drawn from these investigations: Interdisciplinary approaches such as combining behavioural and social sciences with LCA modelling are essential in ensuring that the user behaviour and decisions are adequately considered in LCA. Future research should particularly focus on developing further approaches of combining LCA with behavioural and social science research. This also includes concepts for integrating quantitative and qualitative primary data on user behaviour into LCA. For a holistic focus, future studies should furthermore consider a variety of impact categories in order to examine burden shifting when applying smart technologies.

CRediT authorship contribution statement

Johanna Pohl: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Vivian Frick:** Data curation, Software, Writing – review & editing. **Anja Hoefner:** Data curation. **Tilman Santarius:** Funding acquisition, Supervision. **Matthias Finkbeiner:** Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127845.

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3.3 Application of the conceptual framework to the case of smart homes

In this section, the interdisciplinary study design from Publication 2 is further developed and applied in a second case study analysing the environmental effects of smart homes and their relation with user characteristics such as sociodemographics and user motivation. This section contains the following publication:

Pohl, J., Frick, V., Finkbeiner, M., Santarius, T., 2022. Assessing the environmental performance of ICT-based services: Does user behaviour make all the difference? Sustainable Production and consumption 31, 828–838. https://doi.org/10.1016/j.spc.2022.04.003

Supplementary material to this publication is provided in the Appendix of this thesis.

CRediT author statement:

- Johanna Pohl: Conceptualisation, Methodology, Data curation, Investigation, Formal analysis, Software, Writing – original draft, Writing – review & editing;
- Vivian Frick: Conceptualisation, Data curation, Formal analysis, Software, Writing – review & editing;
- Matthias Finkbeiner: Writing – review & editing, Supervision;
- Tilman Santarius: Writing – review & editing, Funding acquisition, Project administration, Supervision.

Results summary:

In a first part, the interdisciplinary study design is presented and applied. Analyses of the results show that both use-related parameters (e.g. size and composition of the smart home, acquisition or reuse of devices, heating temperature), and housing specifics (e.g. living space) differ significantly among the sample. This can also be seen in the environmental assessment results. For GWP, results are heterogenous: having a smart home with smart heating can lead to large savings or additional burden. According to the results, heating behaviour in particular has a large influence on the environmental performance of the smart home for GWP. For Metal Depletion Potential (MDP), having a smart home represents always an additional burden. For this impact category, composition and size of the smart home are especially decisive for the environmental assessment.

In a second part, multiple regression analysis is used to examine whether the environmental assessment results for GWP and MDP can be explained by user motivation or sociodemographics. Results show that a higher level of income and the higher user motives of technology enthusiasm and security predict a higher environmental impact of the smart home for MDP. Results for GWP show, first, that higher user motives consumerism and security predict a higher environmental impact of the smart home. Secondly, higher energy-saving motivation predicts higher GWP net savings, i.e. a lower overall environmental impact of the SHS.

Implications for LCA research and practice include the discussion of the potential of interdisciplinary approaches for LCA method development, data collection and analysis. For practice, recommendations for sustainable design of SHS are derived.

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Assessing the environmental performance of ICT-based services: Does user behaviour make all the difference?

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A B S T R A C T

Reducing overall household energy consumption through the application of information and communication technologies (ICT) can play an important role in the transformation towards sustainable consumption patterns, e.g. through the optimisation of energy-consuming processes. The challenge in the environmental assessment of ICT applications is to also consider their use-specific environmental effects, as these can be decisive for overall results. Using the example of smart heating, we therefore analyse the environmental performance of a sample of 375 smart home systems (SHS) in Germany and show how the life cycle assessment (LCA) can be extended to include various use-specific effects such as choice of products and individuals' behaviour when using the product. In an interdisciplinary study design, we combine life cycle modelling and behavioural science to systematically include use-specific parameters into the modelling, and to interweave these results with user characteristics such as sociodemographics and user motivation. Our results are heterogenous: For the impact category Climate Change (GWP) we find that having smart heating can lead to large savings in particular cases. On average, however, smart heating does not lead to significant benefits for GWP, but neither does it represent an additional burden. For Metal Depletion Potential (MDP), we find that smart heating is always an additional burden, as heating optimisation has almost no reduction potential for MDP. Our results have a wide range due to large differences in use patterns in the sample. Depending on the impact category, both number of devices of the SHS as well as heating temperature are decisive. Regression analysis of our assessment results with user characteristics shows that differences in MDP and GWP of SHS size can be explained by income, and, in addition, differences in GWP of net heating energy savings can be explained by user motivation. Our results thus underline that the standard scenarios for user behaviour assumed in LCA modelling should be well justified. Future interdisciplinary research should further explore the links between use-specific approaches in LCA and users' environmental behaviour and motivation.

1. Introduction

Information and communication technology (ICT)[1] has the potential to reduce resource and energy demand (Sui and Rejeski, 2002). By using ICT-based services, either processes and thus resources and energy use can be optimised, or the fulfilment of a goal/function can be achieved with alternative, less resource-intensive (digital) products, services or processes (Pohl et al., 2019). Examples span from the substitution of traditional with digital media (Amasawa et al., 2018), over forms of telework (Vaddadi et al., 2020) and new types of consumption (van Loon et al., 2015) to digital process management (Gangolells et al., 2016). Also in households, the application of ICT-based services can play an important role in the transformation towards sustainable consumption patterns (Börjesson Rivera et al., 2014). The role of ICT for reducing environmental effects of processes and services has also been addressed in earlier literature reviews. For example, with a focus on indirect energy effects of ICT, Horner et al. (2016) review studies on e-commerce, e-materialisation and telework. Hook et al. (2020) examine the energy and climate effects of teleworking. Wilson et al. (2020) focus on digital consumer innovations and their emission reduction potential in areas such as mobility, food or energy. It follows that net

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[1] Abbreviations: EoL – End-of-life; FU - Functional unit; GWP - Climate Change; ICT - Information and communication technology; LCA - Life cycle assessment; MDP - Metal Depletion; SHS - Smart home system.

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environmental benefits from the application of ICT-based services are not a priori certain: its application may also lead to an intensification of resource and energy use. On the one hand, this may be due to the fact that an environmental mitigation effect is not an integral part of the service, and thus its operation leads to an increase in electricity demand (Røpke et al., 2010). On the other hand, it may be due to counteracting environmental effects from the application of the respective services, which may exceed the service's optimisation effects (Horner et al., 2016). Hence, user behaviour plays a particular role in the environmental performance of ICT-based services (Bieser and Hilty, 2018).

More precise insights into the role of user behaviour for the overall environmental performance of household appliances can be gained from other disciplines. From a social science perspective, Gram-Hanssen (2013) investigates socio-technical factors that have an influence on residential energy demand. Based on empirical and statistical data, the author identifies four factors that are decisive for overall energy demand: number and size of the appliances, energy efficiency of the technology itself, and related user behaviour. In the case of heating, behavioural aspects are at least as important as the energy efficiency of the technology itself, and in the case of electricity consumption number and use of appliances in the household are particularly relevant. Sociodemographic factors like age, income and education may also play a role in both heat and electricity consumption (Gram-Hanssen, 2013). Other studies show that factors such as user motivation and values (Nilsson et al., 2018), personal beliefs (Girod et al., 2017) and intentions (Ahn et al., 2016) influence the use of appliances and their effects on residential energy consumption. However, regarding individuals' environmental impact, Moser and Kleinhückelkotten (2018) show that income plays a greater role than environmentally friendly intentions. Changes in energy demand related to the way the SHS is used is also examined from the perspective of user adoption of new technologies. In addition to the identification of social barriers that hinder SHS adoption (Balta-Ozkan et al., 2013), this also includes questions about acceptability & usability, user needs (Wilson et al., 2015) and domestication processes (Gram-Hanssen and Darby, 2018; Hargreaves and Wilson, 2017). For example, Hargreaves et al. (2018) show that forms of adaptation also include using only some or none of the features offered by the SHS, which could lead to the technical energy saving potential of the SHS not being fully realised. Chang and Nam (2021) find, however, that the intention to use smart home services is particularly high among those who prefer energy control services. Sovacool et al. (2021) find conflicting practices regarding energy savings and emphasise the link between knowledge about the SHS and its acceptance and diffusion. From these findings, it can be concluded that a holistic environmental assessment that covers effects along products' life cycles as well as their application and use is essential.

With regard to life cycle assessment (LCA), integration of variances in user behaviour is repeatedly cited as one of the most urgent methodological challenges (Finkbeiner et al., 2014; Hellweg and Milà i Canals, 2014). However, a systematic exploration of use-specific aspects and their inclusion into the LCA is still in its infancy (Pohl et al., 2019). Often, poor availability of data is cited as a reason (Börjesson Rivera et al., 2014; Gradin and Björklund, 2021; Miller and Keoleian, 2015). Another reason is that LCA studies often focus on the narrow product system (Kjaer et al., 2016) and apply standardised default use phase modelling. Thus, variations in product application are ignored (Geiger et al., 2018). In order to integrate these use-specific aspects into the LCA, both a solid understanding of user behaviour in the specific context (Polizzi di Sorrentino et al., 2016), and a theoretical concept of how these aspects can be better integrated into the LCA (Pohl et al., 2019) are necessary. More specifically, as shown in previous research, definitions of goal and scope are crucial when integrating use-specific aspects into the LCA: For instance, in order to integrate aspects of prolonged product service life into the LCA, Proske and Finkbeiner (2020) show the importance of defining goal, functional unit (FU) and system boundaries. Likewise, Pohl et al. (2021) highlight that definitions of product system, system boundaries and FU are crucial when integrating user decisions such as choice of devices and services into the environmental assessment. In order to use LCA to address rebound effects or shifts in consumption patterns from circular economy initiatives, Niero et al. (2021) state that the scope definition is of central importance.

In our study we investigate the environmental performance of ICT-based services, focusing on the interlinkages between variances in user behaviour in LCA and further interferences between the user, the product(s) and the surrounding environment. We do this by analysing the environmental performances of a sample of 375 smart home systems (SHS) that include smart heating in Germany. The research-guiding question is: How do variances in user behaviour influence the environmental performance of the SHS? More specifically, and based on our survey, i) we consider and compare LCA of 375 SHS in Germany that differ in number and size of SHS components, and in SHS settings; and ii) we examine whether our environmental assessment results can be predicted by sociodemographics or user motivation.

Our structure is as follows: In Section 2, we briefly present the state of research on the interplay of user behaviour and environmental assessment and identify methodological barriers in current LCA modelling practice. On this basis, in Section 3 we present the interdisciplinary methodology underlying our study on the environmental performance of SHS. In Section 4, we present our results for the impact categories Climate Change (GWP) and Metal Depletion (MDP) and analyse whether they can be explained by sociodemographic information and user motivation. We discuss relevant findings with regard to use-specific modelling in Section 5 and conclude with implications for future LCA modelling in Section 6.

2. Literature review

On a theoretical level, various authors stress the importance of user behaviour in LCA. Suski et al. (2021) suggest a framework that combines LCA with social practice theory when assessing sustainable consumption and helps to define relevant system boundaries by identifying relevant social practices and their interconnectedness. A similar approach is taken by Niero et al. (2021) for addressing socio-technical dynamics when implementing Circular Economy initiatives. Pohl et al. (2021) describe the systematic inclusion of user decision and behaviour in environmental modelling based on three use-specific parameters: (i) choice of products in number and size (product parameters); (ii) use frequency and intensity (use parameters); and (iii) sociodemographic information on the user, all of which can have a decisive influence on products' environmental performance. To assess the consumption behaviour of a human being over their lifetime, Goermer et al. (2020) propose a methodological framework that includes both changes in consumption patterns during lifetime and environmental effects from consumed products throughout the product life cycle. Central to all proposals is the shift from an exclusively product-centric focus in the LCA to a service or consumption focus. What has played little role in these concepts so far is the use of information about users other than sociodemographics, e.g. information on lifestyle or user motivation to further characterise LCA results (see e.g. Moser and Kleinhückelkotten, 2018; Wiedmann et al., 2020).

Several case studies include variances in use patterns into their modelling. However, these differ with respect to the goal definition: (i) influence of user behaviour on the environmental performance of products is either investigated only as a boundary condition; or (ii) user behaviour is addressed as relevant to product use when assessing the environmental impact of a product; or (iii) the study directly focuses on the environmental impact of different types of user behaviour on the overall results. For example, Achachlouei and Moberg (2015) use sensitivity analysis to identify the impact on intensity of use of both tablet device and print editions of a Swedish magazine. However, such studies focus mainly on the environmental effects of production, and differences in user behaviour are considered only as a boundary condition (Achachlouei and Moberg, 2015). Amasawa et al. (2018) investigate to what extent changes in book reading activities impact on GWP when comparing paper book and e-book reading. Investigations of reading activities show that substitution is rarely complete and that both paper books and e-books are read, which significantly alters results (Amasawa et al., 2018). Ross and Cheah (2017) investigate how energy use in air conditioning systems depends on different use patterns and show that variances in use patterns can significantly determine the overall result for GWP.

Studies further differ in terms of types of use patterns that are included. Taking the example of three case studies, Daae and Boks (2015) analyse which and how variances in user behaviour are currently addressed in LCA. Depending on the type of product, the authors identify variations in the interaction with the product with regard to (i) handling of the product (Solli et al., 2009); (ii) frequency of use (O'Brien et al., 2009); and, (iii) duration (Samaras and Meisterling, 2008). Furthermore, choice of (by-)products and/or product settings (Shahmohammadi et al., 2019, 2017) can be identified as a forth type of product interaction. In addition, the way the FU is defined varies greatly, highlighting the different degree of focus on the product or product use within the study. These refer either to the use of a certain quantity of a product, e.g. “one wash cycle” (Shahmohammadi et al., 2017), or to the use of the product over a certain period of time, e.g. “delivery and viewing of one year's worth of BBC television” (Schien et al., 2021). Reference to the user or the household is very rarely made in the definition of the FU, e.g. “book reading activities per person” (Amasawa et al., 2018) or “110 m2 apartment space in Germany managed (monitored and controlled) for 5 years” (Pohl et al., 2021). Bossek et al. (2021) refrain from defining a FU at all and use ‘reporting unit’ instead (“life of a human being”). It becomes apparent that not all definitions here allow for inclusion of secondary effects of product use, i.e. intensification of use or expansion of products used, and that comparability across studies may be limited for very specific FU definitions. One solution to this could be the sound definitions of goal and FU that play a prominent role when it comes to integrating user behaviour into an LCA. For a detailed overview of the methodological choices of all the studies identified here, see Table S1, supplementary material 1.

3. Methods

This study investigates the influence of user behaviour on the environmental performance of SHS. In the following section, we outline the underlying methods and operationalisation. We first give definitions for the key terms ‘smart home’, and ‘user behaviour’, and then explain how our interdisciplinary study design was conceptualised and how and where life cycle modelling and the online survey intertwine.

3.1. Definitions, conceptualisation and operationalisation

The term ‘smart home’ summarises networked applications in the home. Depending on the device composition of the SHS, these applications provide a variety of services in the home, such as security, energy management or comfort (Strengers and Nicholls, 2017). From an environmental perspective, applications for room temperature control, lighting control or optimisation of overall energy consumption can play a role in reducing overall energy consumption in the household (Urban et al., 2016). Smart heating in particular provides some of the greatest potential for energy savings (Beucker et al., 2016). The environmental performance of an SHS is determined from the actual savings of energy optimisation, while accounting for resource demand due to production and operation of the SHS (life cycle effects) and changed user behaviour (Pohl et al., 2021).

The term ‘user behaviour’ describes a variety of behavioural interactions with a product/system. These include choice of products, the user's subsequent behaviour when using the product, and – at the end of the product life cycle – the decision on how to dispose of the product (see Polizzi di Sorrentino et al., 2016). The behavioural sciences, especially environmental psychology, have a long tradition of predicting pro-environmental behaviour, especially energy saving, but also investment behaviour. They find that some behaviour is mainly predicted by socio-economic factors (impact-oriented), whereas other behaviour is better predicted by motives (intent-oriented) (see Geiger et al., 2018). For LCA modelling, it is particularly relevant that user behaviour not only manifests itself during the use phase of a product, but also includes choice of products, services and settings.

In the following section, we will analyse the ICT-based service of smart heating, i.e. we will focus on SHS with smart heating. To break down how and to what extent user behaviour may affect the environmental performance of an SHS, we apply the conceptual model “The user perspective in LCA” (Pohl et al., 2021). The use-specific parameters that we have included into the modelling are shown in Fig. 1. Their integration in the LCA and operationalisation in the survey are summarised in Table 1.

Smart heating devices and SHS infrastructure are at the centre of our product system. Other SHS components that are used in parallel with smart heating devices are also included in the product system. Our model also considers whether these devices were newly acquired/replaced or were already in place. The type of connection the SHS uses (WiFi, other radiofrequency) is also considered. Heating energy demand is affected by applying the smart heating function in two ways: through heating optimisation and through changes in heating behaviour in the home (i.e. variations in the number of rooms that are heated and differences in the temperature level). Since the SHS is operated within an existing and occupied living space, additional information about the living space as well as the people living there can play a role in the context of the system's environmental impact. Information on building type, size of living space and type of heating system is used to calculate total energy savings due to the application of the SHS. Information on sociodemographics and user motivation is used ex post for regression analyses. With this, we want to investigate whether the results from our environmental assessment can be explained by user characteristics. We base our analysis on a previous study by Pohl et al. (2021) and use the sample and inventory data from that study.

3.2. Online survey

The online survey is used to collect (i) primary data from the user about their individual SHS composition, heating behaviour, and housing situation; and (ii) further information on user characteristics, such as information on sociodemographics and user motivation.

3.2.1. Survey sample & procedure

First, the 8149 potential participants who opened the survey link were asked whether they use a SHS with smart heating control (screening). Of these, 644 people (7.9%) confirmed that they used this type of SHS and completed the entire questionnaire. Because 269 participants were excluded due to inconsistent responses or missing information, the final sample size was $N = 375$. The final sample compared to the total of potential participants is roughly equivalent to the percentage of 5.3% smart home users in Germany at the data collection period (Statista, 2019). The high exclusion rate can be explained by the fact that, especially in online surveys and when using a screening question that includes only a small number of people, the number of misreporting is particularly high (Chandler and Paolacci, 2017). We discuss this high exclusion rate in more detail in our adjacent publication (Frick and Nguyen, 2021). The questionnaire consisted of five sections: It started with questions about the participants' motivations for using an SHS. Then followed questions about the SHS composition (number of devices, type of connection) and about housing specifics (e.g. living space, source of heating energy). This was followed by questions on

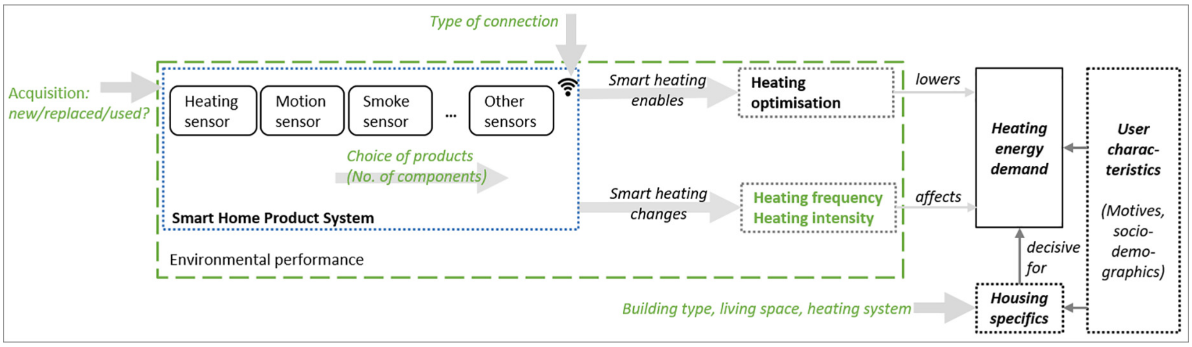

Fig. 1. Conceptualisation: how user behaviour impacts on the environmental performance of a SHS. Use-specific modelling parameters are marked in green (own work, adapted from Pohl et al., 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

heating behaviour (temperature levels in sleeping and living rooms, daytime and night-time). At the end of the survey, sociodemographic information was obtained. As we use the sample from a previous study by Pohl et al. (2021), detailed description of survey sample and procedure can be found in that study. The online survey questions are provided in supplementary material 2. The quality of the questionnaire was ensured by discussing it with experts in the field and testing and revising it with a convenient sample of few participants.

3.2.2. User motivation

The different dimensions of the motivation to use the SHS were created based on the Consumption Motivation Scale by Barbopoulos and Johansson (2017). A shortened version with 21 items adapted to SHS was developed, assessing the original seven consumption motives (for details see Frick and Nguyen, 2021). On a five-point Likert scale, the participants stated how strong their different motives were to use the SHS. Frick and Nguyen (2021) applied cluster analysis to identify four distinct user motives in the smart home: energy-saving, security, technology enthusiasm and consumerism. The energy-saving motive summarises the financial and environmental benefits of energy saving of the SHS. The six items measuring the motive showed high reliability (Cronbach's α = .88). The security motive covers the aspects of protection or control over the apartment/house (α = .89). Technology enthusiasm includes the pleasure of using the product, as well as comfort as a reduction of (physical) effort (α = .83). The consumerism motive describes the will to consume goods that serve the purpose of establishing identity, social acceptance and recognition, but also hedonistic need satisfaction (α = .89).

Table 1
Use-specific information, their operationalisation in the survey and integration in the LCA.

Use-specific information	Operationalisation in the survey	Integration in the LCA
Primary data for LCA modelling		
Smart heating component	Number of devices	Definition of product system
Other SHS components (system expansion)	Device type and number of devices	
Type of connection	WiFi or other type of connection	
Acquisition of SHS components	New acquisition of devices [new/replaced/kept in use]	Scope: production phase from devices already in place is excluded
Heating behaviour	Room temperature [day and night; sleeping and living rooms]	Additional expenditures in the model (see Pohl et al., 2021 for details)
Housing specifics	Building type [apartment/house], living space, type of heating fuel	Proportional heating energy savings due to the SHS application (see Pohl et al., 2021 for details)
User characteristics for regression analyses		
Sociodemographic information	Gender, income, education of SHS users	Ex post: relationship of assessment results with sociodemographic information
User motivation	Consumption Motivation Scale by Barbopoulos and Johansson (2017)	Ex post: relationship of assessment results with user motives

3.3. Life cycle assessment

The environmental impact of each SHS is assessed by performing an LCA based on ISO 14040 (2006).

3.3.1. Aim and scope

The aim of the LCA is to assess the environmental performance of a particular SHS operated in a household in Germany related to one resident. The FU was defined as “providing the service of energy management in a residence for one resident over the period of one year”. Based on the analyses of an average SHS in Germany (Pohl et al., 2021), we include a total of 10 components into the SHS product system. Definition of product system, system boundaries and study scope is taken from Pohl et al. (2021). Environmental impacts from the production of SHS devices are only included in the assessment if the devices were newly acquired. As in Pohl et al. (2021), we use the smart device control unit “X1” as a weight-based proxy device for all components of the SHS.

3.3.2. Inventory analysis & impact assessment

We used GaBi LCA software and the GaBi database Service Pack 39. The majority of our inventory data is adopted from Pohl et al. (2021), where further details on technical data (weight, load) of the different components of the SHS can be found. We assumed that all devices run 2 h per day under full load and 22 h per day under standby (IEA 4E, 2019). For average savings of heating energy through the energy management function of the SHS we assumed 4% of the household's annual heating energy demand (Rehm et al., 2018). This assumption was necessary because we did not have access to the energy consumption data of each SHS user. Calculation of the annual heating energy demand of each household was based on housing specifics from the online survey using the approach by Pohl et al. (2021). We provide results for the impact categories Climate Change (GWP, ReCiPe 2016 v1.1 (H)), and Metal Depletion (MDP, ReCiPe 2016 v1.1 (H)).

3.4. Statistical analysis

We statistically analysed relationships between the online survey data and LCA results for GWP and MDP using multiple regression analysis to predict LCA results by sociodemographic data and user motivation. We performed a per capita analysis. For this purpose, we had to convert some values from the data for the entire household for respondents living in a multi-person household. This concerned income, living space and the number of devices in the SHS. To increase the comparability of results across the study, we weighted the corresponding values per person depending on their age (as opposed to equally weighting all persons in the household), following the approach of Kleinhückelkotten (2016). The respondent was included in the calculation with a factor of 1, other household members at the age of 18 and older with a factor of 0.5, and household members younger than 18 with a factor of 0.3.

4. Results

First in this section, we describe the SHS composition and housing specifics per capita of our sample. Second, we present per capita results on the environmental performance of the SHS for the impact categories GWP and MDP. Third, we analyse to what extent sociodemographic factors of the sample and different user motives may play a role in environmental performance.

4.1. The SHS sample

The compositions of our sample's 375 SHS and related use-specific modelling parameters (see Fig. 1) such as number of devices in the SHS, acquisition of devices, type of connection and housing specifics are described on a per capita basis. See Table 2 for an overview.

Based on our sample, the SHS consists of a total of M (SD) = 4.79 (2.45) components per capita on average. The smart heating component is always included, as it was a precondition for being included in the sample, followed by control unit and smart plug. A central switch is the least frequently present. Almost 3% of our sample report that their SHS is composed of 10 different components, while 8% state that their SHS consists only of the smart heating component. Since different components are present several times in the same system, the SHS consists of a total of M (SD) = 7.52 (5.27) devices per capita on average. Both the maximum value of 34 devices per capita and the minimum value of 0.40 devices per capita are indicated once. The latter value comes about when the SHS is composed of only a few devices while there are more (weighted) people than SHS devices in the household. In most cases (63%) all devices were newly purchased. In some cases, parts of the SHS were already installed (30%), and in others, the entire set of devices was present and no new devices had to be purchased (7%). In most cases (83%), WiFi is the prevailing communication standard. See Table S2, supplementary material 1 for a detailed overview.

Average heating temperature of our sample is reported at M (SD) = 19.4 (1.37) degrees Celsius. The maximum heating temperature of 24 degrees Celsius is stated twice and the minimum value of 16 degrees Celsius is stated four times. The majority of SHS users live in a 1–2 family home (62%). Considerably fewer people (38%) indicate that they live in an apartment in a building with 3 or more apartments. A total of 235 people (63%) state that they are the owner of the house or apartment. The average per capita living space is reported at 66.3 (SD = 23.43) m^2. Both the maximum living space per capita of 210 m^2 and the minimum value of 20 m^2 per capita are indicated once. The distribution by heating system is more complex. We distinguish type of heating system both by power (< 20 kW in 1–2 family homes, 20–120 kW in apartment houses) and by heating fuel. According to the sample, both 1–2 family homes and apartments are predominantly heated with gas (60% of family homes, 53% of apartments) and oil (19% of family homes, 18% of apartments).

4.2. Environmental performance of the SHS

The environmental performance results of our sample's 375 SHS are depicted in Fig. 2 and in Table S3, supplementary material 1.

For GWP, the environmental performance of the SHS varies widely from −991 kg CO_2 eq and 804 kg CO_2 eq per capita per year. For a slight majority of cases (55%), having an SHS that contains smart heating leads to overall reductions (M(SD) = −35 (240) kg CO_2 eq per capita). However, there are large differences between the different fractions that make up the overall environmental performance and these are strongly tied to variances in user behaviour: (i): Life cycle effects: SHS production and operation sums up to M(SD) = 80 kg (24) CO_2 eq per capita. Slightly more than half of this is accounted for by production and operation of smart heating components and SHS infrastructure; the remaining is accounted for by the presence of other components in the SHS. There are large differences within the sample, depending on the number of devices present, i.e. size of the SHS. (ii) Heating optimisation: according to our model, the application of smart heating control always leads to savings (M(SD) = −104 (43) kg CO_2 eq per capita). The differences in the absolute amount of heating energy saved depend on the size of the living space. The larger the living space, the greater the absolute savings potential. (iii) Heating behaviour: Variances in heating behaviour also lead to changes in heating energy demand. There are slightly lower heating temperatures on average in the SHS sample compared to the control group, leading to small overall savings on average (M(SD) = −11 (237) kg CO_2 eq per capita). However, differences in heating temperature are far greater, as can be seen from the high standard deviation, suggesting very large differences in individual heating behaviour. To sum up, our results for net savings for GWP show that almost 77% of an SHS's technical saving potential is equalised by production and operation of the SHS. Furthermore, heating behaviour has a great influence on environmental performance for GWP.

For MDP, the environmental impact is above zero on average (M(SD) = 0.97 (0.8) kg CU eq per capita), which means that the introduction of an SHS poses an additional environmental burden

Table 2
Description of average smart home composition and housing specifics per capita.

Average smart home composition	*No. of devices M (SD)*	*Housing specifics*	
Radiator thermostat	2.4 (1.4)	Heating temperature M (SD)	19.4 (1.37) °C
Humidity sensor	0.8 (1.5)	Living space M (SD)	66.3 (23.43) m^2 per capita
Door/window sensor	0.5 (0.9)	House type	61.6% 1-2 family home
Motion sensor	0.6 (0.9)		37,9% apartment
(Security) Camera	0.4 (0.7)		0.5% other
Smoke detector	0.9 (1.3)	Heating energy source	58.9% gas
Wireless intercom system	0.2 (0.4)		19.2% oil
Smart plug	0.8 (1.2)		11.0% electricity
Switch	0.3 (0.6)		7.1% other (e.g. district heating)
Control unit	0.5 (0.4)		3.8% solid fuel

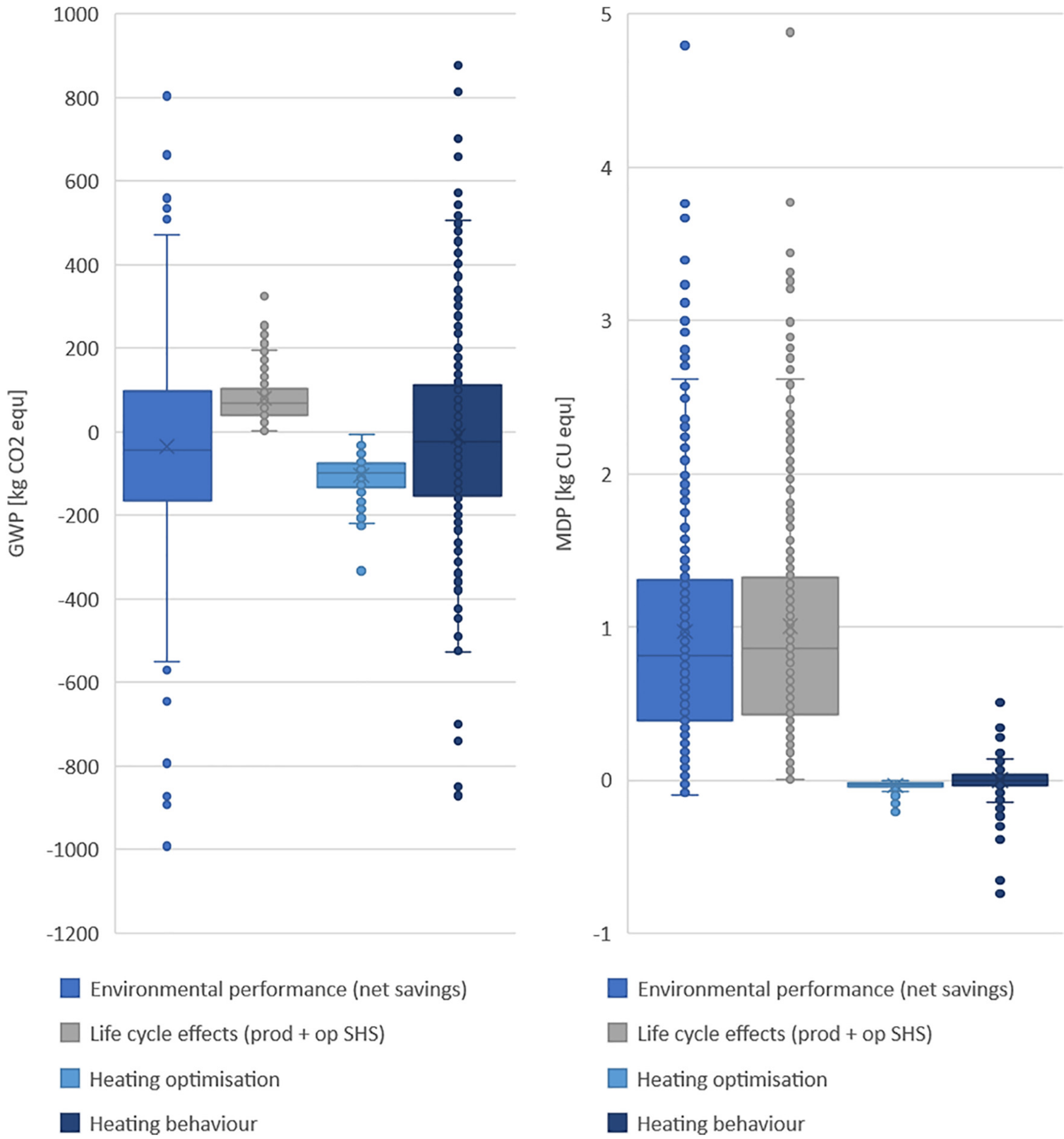

Fig. 2. Boxplot Environmental performance SHS per resident for GWP (left) and MDP (right).

for 98% of our sample. This is due to MDP originating almost solely from material input and production. Minimal reductions of MDP are due to heating optimisation and heating behaviour changes. However, the saving effects for MDP are very small and are not considered significant. For 2% of our cases ($N = 9$), the introduction of the SHS still lead to an overall reduction in MDP. These reductions are due to the fact that these participants reported that all devices connected to the SHS were already in place when the SHS was commissioned, thus the environmental effects from material input and production of these devices was not included in the impact of the SHS. Furthermore, these participants also reported very low heating temperatures, leading to minimal reductions of MDP from overall heating energy demand. To sum up, for MDP the composition and size of the SHS is decisive for the environmental assessment, and effects from heating behaviour and heating optimisation do not play a significant role.

Our results furthermore show the influence of various other factors that can be directly or indirectly related to user decisions. Whether devices of the SHS were already in place or were purchased specifically can have an impact on the SHS's overall environmental impact, especially for MDP. According to our sample, for MDP, life cycle effects are reduced by 46% for users incorporating existing equipment into their SHS. For GWP, this intervention results in a reduction in life cycle effects of 23% on average. Moreover, as already pointed out, size of living space plays a key role in the environmental assessment here. On the one hand, it can be observed that the larger the living space, the larger the life cycle effects for GWP and MDP and thus the environmental impact for MDP. On the other hand, the larger the living space, the greater are the savings from smart heating, and the stronger the effects from heating behaviour for GWP. However, since heating behaviour can contribute to the overall reduction of heating energy demand as well as to its increase, no clear association for the influence of living space on the overall environmental impact for GWP can be identified. For example, for the most commonly reported per capita living space of 60 m^2, the assessment results for GWP range from −504 to 560 kg CO_2 eq. In summary, we find significant differences in the characteristics of the SHS and resulting environmental impact that can be traced back to variances in user behaviour (i.e. choice of products as well as heating behaviour) and housing specifics (i.e. living space). This can also be seen in the large standard deviations for both GWP and MDP.

4.3. Linking environmental performance to user's lifestyle and intention

We further investigate whether the environmental effects from producing and operating the SHS as well as the environmental performance of the SHS can be explained with sociodemographic information and/or user motivation.

Multiple regression analysis (Table 3) shows that a higher level of income predicts higher environmental life cycle effects from producing and operating the SHS (β = 0.24 for GWP, β = 0.21 for MDP). We also found a gender effect, shown by higher environmental effects among male users (β = 0.11 for GWP, β = 0.18 for MDP). For GWP, also age predicts higher life cycle effects (β = 0.13). In addition, the higher the user motives technology enthusiasm (β = 0.17 for GWP, β = 0.17 for MDP), and security (β = 0.26 for GWP, β = 0.25 for MDP), the higher the life cycle effects from producing and operating the SHS. Education level, energy saving and consumerism motives did not predict life cycle effects for GWP or MDP.

Next, we investigate the relationship with regards to overall environmental impact of the SHS. Similar to the above analysis for MDP, the multiple regression model (Table 4) shows that the environmental impact of the SHS for MDP can be explained by income (β = 0.22), gender (β = 0.17) and by user motives technology enthusiasm (β = 0.18), and security (β = 0.24). Again, the greater the income or the higher the technology enthusiasm and security motives, the higher the environmental burden of the SHS for MDP. This is not surprising, as the environmental impact for MDP is dominated by the production phase. Thus, the SHS size is equally decisive for its environmental impact. Age, education level, energy saving and consumerism motives did not predict MDP. The picture is somewhat different for the environmental performance for GWP. The multiple regression model (Table 4) shows that the environmental performance of the SHS for GWP can be predicted by the user motives consumerism (β = 0.17), energy-saving (β = −0.19) and security motivation (β = 0.14). This means that the higher the consumerism and security motive, the higher the environmental impact of the SHS for GWP, i.e. the lower the net savings from heating energy optimisation. The higher the energy-saving motivation, the better the environmental performance for GWP, i.e. the higher the net savings. We also found a gender effect, shown by higher environmental impact among female users (β = −0.13). This may be because women reported higher room temperatures. In contrast to the above analyses, income did not predict the environmental impact for GWP.

Finally, we analyse the relationship between GWP from overall (optimised) heating energy demand and socioeconomic characteristics and user motivation to contextualise our results. Our results (Table 5) show that the size of living space can be explained by income (β = 0.48) and age (β = 0.12). This means that, according to our sample, the higher the income and the older the user, the larger the living space. We also found a gender effect, shown by larger living space among female users (β = −0.11). Secondly, also for overall heating energy demand in households with smart heating, we found that the higher the income, the larger the GWP from overall heating energy demand (β = 0.44). Again, we found a gender effect, shown by higher environmental effects among female users (β = −0.13). This may be because women reported larger living space per resident. User motivation did not predict living space or heating energy demand. Bringing these results together with our analysis of environmental performance of SHS, we can conclude that SHS environmental performance for GWP is rather driven by user motivation and that income does not play a decisive role. However, income remains the most important predictor of the level of GWP from overall household heating energy demand.

5. Discussion

In the following section, we discuss our key findings with regard to certain modelling aspects and deduce implications for research and practice.

5.1. The complex role of user behaviour in the smart home

Our key findings point to the complex role of user behaviour in the smart home. As our results for GWP show, having smart heating does not lead to significant benefits on average, though neither does it represent an additional burden. However, in certain cases, having smart heating can lead to large savings or additional burden. For MDP, having an SHS is always an additional burden, as heating optimisation has almost no reduction potential for MDP. Depending on the impact category, both number of devices of the SHS as well as heating temperature are decisive for the overall results. Both parameters describe user behaviour in the smart home, on the one hand with regard to choice of products and on the other with regard to heating behaviour. As can be seen from the high standard deviations of our results, these sometimes considerably vary within our sample, suggesting very heterogeneous user behaviour. This also becomes apparent from detailed analysis of the individual results of the sample, which, for GWP for example, sometimes show very high saving effects, but sometimes also high additional burden – depending on heating temperatures and the number of devices in the SHS. It can thus be seen that, above all, variances in heating behaviour are crucial for the overall results. However, if the use parameters to be included in the LCA are not sufficiently validated and cannot be contextualised, as we have done here with the help of descriptive statistics, the uncertainty of the results may increase. Overall, our findings confirm that the inclusion of user behaviour into an LCA could be a potential source of uncertainty (Baustert and Benetto, 2017; Miller and Keoleian, 2015) that should be analysed in a methodologically appropriate way. Accordingly, the default scenario for user behaviour assumed in the modelling should be well justified.

Table 3
Regression analysis: Environmental effects from SHS production and operation for GWP & MDP, socioeconomic information and user motivation.

Production and operation SHS	GWP					MDP				
	B	SE	β	t	p	B	SE	β	t	p
Socioeconomic information										
Age	0.495	0.201	0.125	2.463	0.014 *	5.97e-03	3.119e-03	0.098	1.912	0.057 .
Gender (1 female, 2 male)	12.493	5.774	0.11	2.164	0.031 *	3.08e-01	8.971e-02	0.176	3.435	0.0007 ***
Education	1.533	1.81	0.042	0.847	0.398	3.57e-02	2.813e-02	0.063	1.269	0.205
Income share	0.015	0.003	0.237	4.737	3.21e-06 ***	2.14e-04	5.018e-05	0.215	4.254	2.72e-05 ***
User Motivation										
Energy-saving	−1.381	4.015	−0.022	−0.344	0.731	−3.80e-02	6.24e-02	−0.039	−0.609	0.543
Consumerism	−2.602	2.519	−0.065	−1.033	0.302	−4.71e-02	3.91e-02	−0.07	−1.204	0.229
Technology enthusiasm	11.845	4.627	0.169	2.560	0.011 *	1.88e-01	7.19e-02	0.167	2.501	0.013 *
Security	11.951	2.763	0.259	4.325	2.01e-05 ***	1.75e-01	4.29e-02	0.246	4.073	5.79e-05 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

Table 4
Regression analysis: Environmental performance SHS for GWP & MDP, socioeconomic information and user motivation.

Environmental performance SHS	GWP					MDP				
	B	SE	β	t	p	B	SE	β	t	p
Socioeconomic information										
Age	−0.300	1.024	−0.016	−0.293	0.769	5.83e-03	3.09e-03	0.097	1.886	0.06018 .
Gender (1 female, 2 male)	−71.052	29.437	−0.131	−2.414	0.016 *	2.93e-01	8.90e-02	0.169	3.292	0.00110 **
Education	−3.721	9.229	−0.021	−0.403	0.687	3.18e-02	2.80e-02	0.057	1.139	0.25556
Income share	0.022	0.016	0.071	1.323	0.187	2.13e-04	4.98e-05	0.216	4.282	2.42e-05 ***
User Motivation										
Energy-saving	−56.835	20.470	−0.188	−2.777	0.006 **	−5.96e-02	6.19e-02	−0.062	−0.964	0.336
Consumerism	35.074	12.842	0.169	2.731	0.007 **	−3.40e-02	3.88e-02	−0.051	−0.876	0.382
Technology enthusiasm	25.201	23.589	0.076	1.068	0.287	1.91e-01	7.13e-02	0.179	2.683	0.008 **
Security	31.196	14.089	0.142	2.214	0.027 *	1.70e-01	4.26e-02	0.242	4.003	7.71e-05 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

It becomes apparent that size of living space, another factor related to the user, plays a central role in our analysis, even though it is outside the product system. This is because living space is a key parameter for determining heating energy demand, which is the service's application area. From this it follows that other factors related to the user which are clearly outside the LCA model can nevertheless have an indirect influence on the environmental assessment results. With regard to the inclusion of variances in user behaviour, attention should therefore also be paid to use-specific factors from the individual services' application areas.

Furthermore, our investigation on the linkages between environmental performance of SHS, sociodemographics and user motivation shows that it is not possible to clearly answer whether income or user motivation have more explanatory power. In our study, we find both motives (technology enthusiasm, security) and socioeconomic factors (income) that are more likely to be associated with increased energy and resources demand as a predictor for the level of environmental impact due to the size of the SHS. For the environmental performance for GWP, we find no significant relation with income, indicating that GWP is independent from their user's level of purchasing power. However, we find a positive relation with consumerism and security motives, and a negative relation with the energy-saving motive. Thus, our results show that a general analysis of the environmental advantages and disadvantages of an SHS is not helpful; it should be much more focused, e.g. on specific user groups. User characteristics should also be considered when deducing recommendations for policy and practice, for example by explaining the context of use, showing limits of scalability or defining specific target groups. The positive relation of the environmental performance for GWP with consumerism and security motives, and negative relation with the energy-saving motive implies, for example, that the GWP reduction potential of smart heating is only realised if users are motivated to save energy. Since this pro-environmental value orientation only applies to a small part of the population, see e.g. a study on market share of green products in Germany (Steinemann et al., 2017), this clearly shows the limits of scalability. The countervailing high consumption and security motives show another aspect of the limits of scalability. According to our analysis this is mainly due to higher device purchases when security motives are high. These limits could be overcome by implementing energy sufficiency strategies (e.g. Best et al., 2022) that are independent of user motivation. For example, policy makers could implement incentive structures that promote energy saving independently of environmental motives, for example through sustainability-oriented pricing policy. Further, developers could design SHS that help users save energy regardless of their use intentions (e.g., by energy saving default settings). We also find that income (explainable by living space) largely determines the level of overall (optimised) heating energy consumption per resident. This shows the general limitations of the energy saving potential through smart heating, which are independent of whether the user intends to save energy or not.

Our findings replicate findings that energy savings are only realised if an energy-saving motive is given as shown by Henn et al. (2019) for smart metering devices and tie in with a strand of consumer research showing that affluence is by far the strongest determinant for environmental (and social) impacts from consumption (Jones and Kammen, 2011; Wiedmann et al., 2020). Further, our findings relate to research on sufficiency measures in the heating sector showing that the necessary GWP reductions from the residential sector to tackle climate change can only be achieved if the living space per person is also significantly reduced (Cordroch et al., 2021; Lorek and Spangenberg, 2019).

5.2. Strength and limitations

We carefully defined our FU to allow secondary effects of product use (i.e. variances in size of the SHS and in heating behaviour) to be included in the modelling while ensuring comparability of results. This means that to maintain the variability and comparability of the definition of the product system in use, we refer to the service provided (i.e.

Table 5
Regression analysis GWP of heating energy demand, living space, socioeconomic information and user motivation.

	GWP of heating energy demand					Living space				
	B	SE	B	t	p	B	SE	β	t	p
Socioeconomic information										
Age	7.50	4.254	0.090	1.763	0.079	0.222	0.090	0.121	2.474	0.014 *
Gender (1 female, 2 male)	−316.26	122.33	−0.132	−2.585	0.010 *	−5.797	2.581	−0.110	−2.246	0.025 *
Education	−13.61	38.352	−0.017	−0.355	0.723	−1.191	0.809	−0.070	−1.472	0.142
Income share	0.603	0.068	0.442	8.816	< 2e-16 ***	0.014	0.001	0.482	10.002	< 2e-16 ***
User motivation										
Energy-saving	−127.04	85.065	−0.095	−1.493	0.136	−1.824	1.795	−0.062	−1.016	0.310
Consumerism	23.70	53.365	0.026	0.444	0.657	−1.057	1.126	−0.052	−0.939	0.348
Technology enthusiasm	57.672	98.028	0.039	0.588	0.557	2.162	2.068	0.067	1.045	0.297
Security	42.150	58.549	0.043	0.720	0.472	1.711	1.235	0.080	1.385	0.167

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

energy management) instead of the product itself. To integrate intensification of use into the LCA, we relate the provision of energy management to time. Further, we have adopted a consumption-based approach (see Sala et al., 2019, p. 11), i.e. we allocate environmental effects from service provision to the final consumer. This decision results from the crucial role that size of living space plays in heating energy demand. We have also tested alternatives to the consumption-based approach, namely relating the service provision relatively per m^2 or per household. However, we decided to apply the consumption-based approach, because the first alternative did not take into account all decisive user-specific influences (namely, the different sizes of living space), and the second alternative did not allow for comparability of results due to different household sizes.

Many of the modelling decisions in our study are based on our survey data, e.g. definition of product system, information on heating behaviour, and information on housing specifics. Online surveys, especially when administered by professional panel institutes as in our study, provide convenient and time- and money-saving recruitment. On the other hand, this approach comes with possible limitations in data quality due to self-reported behaviour for these data. Approaches for data collection that would improve data quality include in-house interviews or living laboratory studies. The latter would offer the possibility of combining the data collection with energy consumption measurements, for example using smart metering. Another limitation is that our sample consists only of SHS users with smart heating, so we cannot make any general conclusions about the various other SHS types on the market. The sociodemographic characteristics and user motivations in our sample are specific to SHS users with smart heating functions in Germany. As no statistical information on the sociodemographical constitution of this population group was available, we did not set quotas for age, income, education level, or gender and therefore the sample is by nature not generalisable to the German population. Another limitation in terms of generalisability of the results is that smart home users can be described as 'early adopters'. These are characterised by, among other things, being better informed, having a higher income and seeing a greater benefit from the adoption compared to mass market adopters (Wilson et al., 2017).

Limitations of our LCA include the use of a proxy device for all devices in the SHS, setting the service life for all devices to five years, and a cradle-to-use modelling approach. In particular, by using a proxy device for all appliances, we were not able to capture the choice of different products in terms of energy and resource efficiency. In addition, we also had to make an assumption regarding the relative optimisation of heating energy through smart heating. Here we decided to make a conservative assumption, based on a study that had actually collected measured data on heating behaviour. Other studies assume higher optimisation potentials for smart heating, but these assumptions are theory-based and a transfer into practice is unclear. Since both production and operation of the SHS devices as well as heating optimisation are crucial for the final results, as we show for GWP and MDP, more precise data would presumably lead to the reduction of eventual uncertainties. Nevertheless, the more exact modelling would be significantly more time-consuming, so that questions of effort and benefit would justifiably arise.

In general, with our study we were able to emphasise the importance of a life cycle approach. We have only presented our results for the impact categories MDP and GWP. However, we were able to show that applying ICT-based services with the goal to reduce processes' energy demand leads to a shift in environmental burden between the impact categories, replicating findings from Cerdas et al. (2017), Ipsen et al. (2019), and Pohl et al. (2021). For impact categories with regional or local impact (e.g. acidification or ecotoxicity), this means that there may also be shifts with regards to affected areas. It is urgently necessary to investigate the influence of digital process optimisation and the role played by user behaviour on other impact categories as well.

5.3. Implications for research and practice

For the integration of user behaviour in an LCA, our study highlights the advantages of an interdisciplinary approach to LCA method development, data collection and analysis. By applying an interdisciplinary concept of how user behaviour and environmental performance of products are linked, it can be ensured that user behaviour in an LCA is addressed in a scientifically sound way. An interdisciplinary approach is also helpful for data collection, as it enables the extensive collection of primary behavioural data and hence enhances the study's informative value. Finally, the joint analysis of environmental assessment results, corresponding sociodemographic information and user motives provides an innovative approach to contextualise LCA results and trends. Based on this, options for action can be identified or certain policy measures can be validated, e.g. for certain target groups. These groups could be, for example as we have done here, based on their motives, e.g. energy saving, consumption, or security. For these groups, environmentally relevant aspects in choice of products and product use could be described. Vice versa, the findings help focus on impactful target behaviours in environmental psychology. Future research should build on this and further explore the links between environmental assessment and user characteristics, user behaviour, or user expectations from the perspective of environmental psychology, science and technology studies or social practice theory. In addition to the sociodemographics and user motives considered here, these can also include user characteristics such as pro-environmental behaviour (Moser and Kleinhückelkotten, 2018), user adoption of technological innovations (Hargreaves et al., 2018), the social situation or the basic value orientation of users (Gröger et al., 2011). The quantitative measurement of pro-environmental behaviour is especially promising for an appliance in more realistic LCA scenarios (Polizzi di Sorrentino et al., 2016). The measurement of impact-relevant behaviour has a long tradition in environmental psychology, can be challenging and complex, and needs to be developed context-dependently depending on the behavioural domain (for a thorough discussion see Lange and Dewitte (2019)). The identification and characterisation of specific user groups (Sütterlin et al., 2011) would also be valuable in order to address their group-specific needs in the housing sector in a more energy-sufficient way rather than increasing dependency on resource-intense technology. Depending on the methodological approach and the sector, these user-driven parameters can be assessed using a broad set of quantitative methods (e.g., surveys to collect primary data on individual consumption behaviour), as in this study, or qualitative methods (e.g., interviews to explore the reasons and rationales behind certain user behaviour), as suggested for example by Suski et al. (2021). All in all, we identified great potential for fruitful collaboration of LCA researchers with the disciplines of and environmental psychology and the social sciences.

For practice, our study highlights the importance of keeping the SHS as small and long-lasting as possible, i.e. minimise system expansion beyond energy management devices and, if possible, integrate existing devices into the SHS. In this way, the environmental impacts associated with material input are kept as low as possible, and the technical saving potential for GWP can be maximised. For GWP, special attention should be paid to heating temperature settings, since these have a great effect on the overall environmental performance. Furthermore, the extent of actual GWP savings depends on the technical savings potential of the SHS. This shows, once more, that there is a need for a standard specifying technical requirements of an SHS. In order to ensure maximum energy savings effects of the SHS, the focus of the standard should be on energy management and define energy-saving default settings. When considering the scalability of individual study results, it should be considered that some of them depend significantly on sociodemographics and/or user motivation and thus only apply to certain user groups.

6. Conclusions

With our study, we investigated the impact of variances in user behaviour on environmental performance of ICT-based services. The contribution of this study is twofold: First, we have shown that the integration of user behaviour in LCA, i.e. how and in which quantities products are used, can have a major impact on environmental assessment results for ICT-based services. For the environmental performance of SHS we find that, for MDP, smart heating is always an additional burden, mainly stemming from resource demand and production of the SHS. It follows that the composition and size of the SHS (i.e. choice of products) is crucial for overall MDP. For GWP, we find that having smart heating does not lead to significant benefits for GWP on average, but can lead to large savings or additional burden in certain cases. This is particularly dependent on both the number of devices of the SHS (i.e. choice of products) and heating temperature (i.e. heating behaviour). Another factor that is indirectly related to user behaviour and has an impact on the environmental assessment result for GWP is the size of the living space. Second, we have demonstrated that both user motives and sociodemographic characteristics have strong effects on the actual outcomes of the analysis for GWP and MDP saving potentials. Thus, combining LCA results with user-specific information beyond mere product use data can make an important contribution to analysis, for example by classifying results, identifying target groups or showing limits to scalability. However, for consistent inclusion of user behaviour throughout all phases of an LCA study, it is important first to consider the potential influence of user behaviour when defining goal and scope. In particular, the definition of a FU decides how extensively user behaviour can be integrated into environmental modelling. Future research should expand interdisciplinary collaboration of LCA researchers with the disciplines of environmental psychology and the social sciences. Implications for practice include measures for sustainable design of SHS.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.04.003.

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4 General discussion of findings, modelling approach and future research

This thesis has investigated how higher-order environmental effects can be integrated into LCA of ICT. The integration of higher-order ICT effects into LCA is of importance when it comes to determining the environmental impact of the application of ICT-based services, e.g. the determination of the environmental saving potential of an application. First, the challenges of including higher-order effects of ICT into LCA studies were systematically analysed (*RQ1*). Second, a conceptual framework for the integration of higher-order effects and user behaviour into LCA modelling was developed according to the identified research needs (*RQ2*). Third, the conceptual framework was applied to the case of smart homes (*RQ3*). Given the cumulative character of the thesis, the core publications presented in Chapter 3 provide answers to the three research questions of this thesis.

In the following Section 4.1, key findings and remaining challenges are presented. In Section 4.2 the modelling approach is discussed in relation to sources of uncertainty, followed by a critical reflection of LCA modelling decisions in Section 4.3. Finally, the transferability of the conceptual framework is discussed in Section 4.4 and, based on the analysis of the case study results and the methodological approach, future research is derived in Section 4.5.

4.1 Key findings and remaining challenges

In the course of this research, a contribution is made to the research gaps identified in Publication 1, as presented in Figure 3: First, the conceptual framework shows a way to capture use-related higher-order effects into LCA through an appropriate definition of goal and scope. Second, the application of an interdisciplinary study design integrating social science perspectives ensures an adequate conceptualisation and analysis of user behaviour in the case of smart homes. And thirdly, the study design also involves the collection of primary data on smart home user behaviour and other user characteristics, which provides a solid database on user behaviour in the smart home.

Whether the inclusion of higher-order effects into LCA of ICT is indicated depends primarily on the study goal and the intended use of the study results. If the application of ICT is being investigated, i.e. if the focus is on the consumption side, higher-order effects should be included in the assessment. Their inclusion, however, is not useful if the focus of the investigation is on the production side, i.e. if ICT devices are to be assessed solely with regard to differences in the sources of raw materials, the production or their design.

For future ICT assessment, three factors can be derived from this research that are decisive when integrating higher-order effects into LCA of ICT:

1. Operationalisation of higher-order effects to specify how possible rebound and induction effects might manifest in the particular application case
2. Integration of higher-order effects in LCA modelling through adequate modelling decisions
3. Solid data basis encompassing both life cycle data on ICT devices involved, and user behaviour data

With regard to the overall environmental performance in the SHS, one finding of this research is that the optimisation effect in the average smart home must be at least 6% of the annual heating energy demand over three years in order to balance out the effects from the production and operation of the SHS. Only then are net savings realised for GWP and PED. This can be largely attributed to the level of induction effects, which accounts for up to 80% of the environmental effects from production and operation. This also becomes clear in comparison with other studies (e.g. Beucker et al., 2016; Dam et al., 2013). These studies partly calculate significantly lower payback times, which is also due to the omission of induction effects in the models. For all other impact categories, the introduction of an SHS posed an additional burden, as environmental effects from producing and operating the SHS are greater than the effects from heating optimisation.

When analysing the individual acquisition behaviour and heating behaviour in the smart home, another finding is that there are large differences within the sample due to the size of the SHS and in particular due to different heating temperatures, leading to large differences in the environmental performance of the particular SHS. It follows that the inclusion of user behaviour in LCA of ICT can increase the uncertainty of the results if the data on user behaviour are not appropriately validated.

Going beyond the classification of use-related higher-order effects of ICT, there are other aspects related to the user and their behaviour that play a central role with regard to the environmental performance of SHS, as investigated in the second case study. In the case of smart heating control, this is primarily the size of the living space, which is central to determining the heating energy demand and is thus also important for determining optimisation effects and rebound effects. With regard to the acquisition of SHS devices, whether devices of the SHS were already in place or were purchased specifically also impacts the environmental assessment. Overall, these findings relate to those from Gram-Hanssen, 2013, who showed that user behaviour is at least as important for reducing heating energy consumption in the household as efficient technology itself.

However, there are still several challenges in integrating higher-order effects into the LCA of ICT that could not be addressed within the scope of this research.

For one, by applying the conceptual framework *The user perspective in LCA*, only a limited number of higher-order effects of ICT can be addressed. This can be attributed to the research approach. When revising the framework of the environmental effects of ICT, the focus was on rebound effects and induction effects, while other higher-order environmental effects such as obsolescence effects, i.e. variances in active service life (Hilty and Aebischer, 2015), were not included. This said, one could argue that obsolescence is a special form of an induction effect, if one considers the successor model as a complementary product that seamlessly follows on from the old model. Indeed, Proske and Jaeger-Erben, 2019 and Proske and Finkbeiner, 2020 show that obsolescence is a relevant topic both with regard to environmental impact of ICT and in terms of LCA method development. Nevertheless, environmental effects related to differences in service life were not part of further research.

Also when developing the conceptual framework, further higher-order effects were not covered. User behaviour was defined and user-driven parameters were categorised based on consumption research (Geiger et al., 2018; Polizzi di Sorrentino et al., 2016). However, as shown by Niero et al., 2021 and Suski et al., 2021 in relation to LCA, there are other theoretical foundations for understanding and modelling consumption, such as social practice theory. Including these concepts would undoubtedly lead to a different structure and composition of the conceptual framework, for example with regard to system boundaries. This might apply in particular to the inclusion of indirect rebound effects, which were not covered in the conceptual framework developed here. As for example Walzberg et al., 2020 show for smart electricity management and information feedback, indirect rebound effects from the use of ICT can be significant.

Another challenge results from choice of the data collection method. In this research, primary data on user behaviour was collected via an online survey. Online surveys are a common approach for the collection of user behaviour data. However, due to missing or incorrect input data this approach is also associated with data quality limitations impacting the uncertainty of the overall modelling results (see discussion in Section 4.2). In order to improve data quality it would be helpful to also use other sources and methods for data collection such as user interviews or living lab studies. Measuring energy consumption in households would also be a way to improve the quality of the data. A collection of suitable data collection approaches is provided in the supplementary publication Pohl et al., 2019b.

4.2 Sources of uncertainty in the modelling approach

In the following, the modelling approach applied in this thesis is analysed in relation to potential sources of uncertainty. The classification developed by Baustert and Benetto, 2017 is used here and parameter uncertainty (Section 4.2.1), uncertainty due to choices (Section 4.2.2), structural uncertainty (Section 4.2.3) and systemic variability (Section 4.2.4) are discussed.

4.2.1 Parameter uncertainty

Parameter uncertainty may arise from the use of data from the online survey. Baustert and Benetto, 2017 point out sources of error that have to be taken into account when using survey data in LCA, namely random errors (e.g. incorrect answers), systematic errors (e.g. biases due to the design of the survey, or linguistic inaccuracies) and approximations in the survey results when handling missing data. Online surveys are a common approach for the collection of user behaviour data. However, due to self-reported behaviour for these data, this method is also associated with limitations in data quality. Thus, random errors could have occured when indicating the number and type of SHS components, the average heating temperatures or further details on the living situation. Other approaches that are less prone to random error are, for example, user interviews or direct measuring of energy consumption in households.

In addition, it cannot be ruled out that systematic errors may have been made in the design of the online survey. However, quality assurance measures were used to avoid this as far as possible. In addition, there were approximations for some variables where information was missing in the sample. In order to keep the error as low as possible, data sets with a large amount of missing information were not included in the final sample.

Parameter uncertainty can also occur when using LCI data from the GaBi databases and ecoinvent databases. In particular for the modelling of the printed circuit board (PCB), which accounts for most of the environmental impacts from production of the SHS for the selected impact categories, it can be seen from Clément et al., 2020 that the unit process "wafer, fabricated, for integrated circuit" in the ecoinvent database v.3 used in this work is subject to a high degree of uncertainty. An uncertainty of 20-25% is determined for the proportion of the wafer in integrated circuits (Clément et al., 2020).

4.2.2 Uncertainty due to choices

Uncertainty due to choices may arise mainly from choices in defining goal and scope, for example regarding the definition of system boundaries, or the definition of the functional unit (Baustert and Benetto, 2017).

In both case studies, the definition of the product system and the functional unit are oriented towards including higher-order effects of ICT in the modelling, with assumptions made about the main functionality in the SHS that may turn out to be wrong. Thus, handling of multifunctionality is another potential source for uncertainty (Kim et al., 2017). That this research considers any additional functions in the SHS as an induction effect rather than as a multifunctional product may also be a source of uncertainty. As analysed in the first case study, the share of induction effects is 79% of total GWP from producing and operating the average SHS. If the induction effects were not included in the model, net saving effects would increase and payback times would decrease. For the 20% savings scenario, this would mean a 14% increase in net savings for GWP over five years and a two-thirds reduction in payback time. Furthermore, net saving effects for GWP would then already occur with annual savings of 4% (instead of only 6%). Similarly, in the second case study, if induction effects were not to be included into the model, environmental performance would improve for those SHS where induction effects are present. On average, this would mean an improvement from M (SD) = -35 (239) kg CO_2 eq to M (SD) = -73 (237) kg CO_2 eq per year.

4.2.3 Structural uncertainty

Structural uncertainty arises from simplified models and, according to Baustert and Benetto, 2017 is only addressed very rarely in LCA. As far as the modelling approach in this study is concerned, potential structural uncertainty can be identified in relation to the application of the conceptual framework. One limitation when developing the conceptual framework is that it is based on consumption research. This could have implications regarding which different higher-order effects are considered in the framework and how they are defined.

With regard to the conceptual framework, this type of uncertainty discussion further concerns the operationalisation of user-driven parameters in LCA. Hence, the operationalisation of rebound effects and induction effects in the two case studies is a potential source of uncertainty. One the one hand, the type of rebound effect and induction effect was defined based on previous research. However, the definition could also be considered selective, as for example only direct rebound effects related to heating behaviour were considered. Further, as pointed out by Coroamă et al., 2020, distinguishing which part of the behaviour change is ICT-induced (i.e. can be considered a rebound effect or induction effect) and which is due to other causes is another potential source of uncertainty. For example, in the case studies all deviations from the average heating temperature in the sample were considered rebound effects, and all SHS components in the SHS besides smart heating control were considered induction effects. Hence all deviations in user behaviour were considered ICT-induced, without actually knowing whether they were or not.

Another source of uncertainty is the simplified LCI model that was applied to the SHS in both case studies. Here, simplification took place in several ways: First, all the different components of the SHS were included in the model using a proxy device. Inclusion took place based on the components' weight, thus assuming similarity in terms of the design of each of the devices and their production. An overestimation of the environmental impacts from production for the SHS can be assumed due to the comparatively high weight share of the PCB in the proxy device. In addition, as pointed out by Clément et al., 2020, the location of the production facility has an influence on the level of GWP, as electricity generation is relevant for this impact category. Here, production was assumed to take place worldwide, with the final assembly taking place in Germany. Hence, the GWP from production could be slightly underestimated, considering that ICT hardware is often produced in countries with a high share of coal-fired power, such as China.

Second, the control unit "X1" was selected as weight-based proxy device representing all other components of the SHS. The PCB was modelled using the wiring board for a laptop mainboard from the ecoinvent database. From comparison with other data sets it can be assumed that the environmental impact of the X1's PCB is slightly overestimated. The analysis of the influence of PCB on the overall results carried out in the first case study showed, however, that even with variations of 90% and 110% of the environmental burden from the production phase, differences in the overall results were not significant.

Third, for the different components of the SHS, technical data on weight were taken from product sheets of one of the largest SHS manufacturers in Germany, and data on load were taken from the International Energy Agency (IEA). This approach thus negated possible differences in size and load between devices from different manufacturers. For a selection of smart heating control devices from different manufacturers, the range of technical data is shown in Table 3. The devices differ in particular with regard to their weight. Device A used in both case studies has the lowest weight in comparison. The environmental effects from the production of this device could therefore be slightly underestimated. In addition,

Table 3: Technical data of radiator thermostats from different manufacturers

Radiator thermostat	Weight [g]	Load [W]	Reference
A	140	0.18	Bosch Thermostat AA
B	193	0.18	Netatmo
C	142	0.18	Homatic IP - evo
D	275	0.18	tado

it was assumed in the first case study, that all devices ran under full load, because the average standby times of smart home devices were unknown. However, sensitivity analysis revealed that changes in the devices' operational energy demand have an impact on the overall results for GWP and PED. If devices only ran only 2h under full load every day, the operational energy demand would be almost halved and thus also GWP and PED from the operation of the SHS. This would reduce the direct effects of the SHS from production and operation by roughly 35%, assuming an overall life time of the SHS of five years. Hence, GWP and PED from production and operation (direct effects) could be overestimated in the first case study. For this reason, a daily standby time of 22 hours was assumed in the second case study. However, due to a lack on actual operational energy demand data, uncertainty remains.

Forth, the environmental impact of data transmission was included using a simplified model of the ICT infrastructure based on data volumes over a certain period of time. As discussed in more detail in Section 4.3, it can be assumed that the environmental impact of the ICT infrastructure on the overall result was estimated conservatively. The case study results show that, given the rather small amounts of data generated by SHS use, the impact from ICT infrastructure is negligible, even with a conservative assumption of the energy intensity per kwH/GB. This was to be expected, as studies on video streaming, for example, show that the environmental impact from production and operation of the end-user devices is clearly predominant (Schien et al., 2021; Suski et al., 2020).

Finally, transportation and EoL were not considered in the product life cycle. This means that the direct effects of the SHS may be slightly underestimated due to the exclusion of the transportation phase, and that due to the exclusion of the EoL phase, and depending on the actual EoL scenario, any credits for the individual impact categories were not taken into account.

4.2.4 Systemic variability

Systemic variability refers to the "uncertainty in human decisions" (Baustert and Benetto, 2017) and is of central concern when including variances in user behaviour into LCA of ICT. Depending on the overall study goal, the question is how representative and generalisable the included set of user behaviour data is, thus underlining the necessary validation of user behaviour data before their integration into LCA.

Both case studies use the same set of data on user behaviour that was collected by means of an online survey. Thus, both the qualitative limitations with regard to data quality that go hand in hand with the data collection method (see "Parameter uncertainty", Section 4.2.1), and any limitations stemming from the formation of a representative sample also apply to the LCA results and their generalisability.

Systemic variability due to the inclusion of user behaviour data is particularly apparent in the second case study. When analysing individual user behaviour, large scattering was found for the number of SHS devices (M (SD) = 7.5 (5.3)), heating temperature (M (SD) = 19.3 (1.4)°C) and size of living space (M (SD) = 66.3 (23.43) m^2), as can be seen from the large standard deviations. Consequently, this also applies to the overall assessment result for GWP and MDP, which means that no general conclusions can be drawn from the individual assessment results.

In the first case study based on the online survey, the average SHS in Germany was analysed. However, as can be seen from the comparison of the sociodemographic data of the smart home sample and control group (Table 1 in Publication 2), the smart home sample does not constitute a representative sample of the German population. Thus, the data on user behaviour and consequently the overall assessment results are only valid for a specific group of users. Regarding the SHS, as discussed in the second case study, the group of smart home users can be described as *early adopters* (Wilson et al., 2017), i.e. conclusions can only be drawn for this specific user group.

However, this discussion also shows that systemic variability can be minimised by using average data on usage behaviour that is representative of the population/ the reference group. In other cases, such as the example mentioned by Baustert and Benetto, 2017, which refers to the behaviour of a specific professional group, systemic variability could also be minimised if the data on usage behaviour is based on a representative sample.

4.3 Implications for LCA modelling

Assessing the environmental effects of ICT-based services with LCA comes with methodological challenges (see Section 1.1 for a detailed description). With the aim of addressing the challenges that are related to the integration of higher-order effects into LCA of ICT, the conceptual framework *The user perspective in LCA* was developed and applied to the case of smart homes. In the following, this section discusses for which research questions the inclusion of higher-order effects in the LCA modelling is suitable (Section 4.3.1), as well as the resulting modelling implications with regard to the definition of functional unit (Section 4.3.2), product system (Section 4.3.3) and multifunctionality (Section 4.3.4).

4.3.1 Study scope

From an LCA perspective, integrating higher-order effects of ICT in LCA is a matter of integrating variances in user behaviour into the modelling. Here, the conceptual framework can provide guidance in identifying user-driven parameters and the corresponding parts of the goal and scope definition in LCA in order to adequately address use-related higher-order effects. For study goals that focus on the investigation of product use behaviour, e.g. in which possible environmental saving potentials from the use of online shopping are investigated, or as in the case studies of this thesis, heating behaviour in the smart home, the application of the conceptual framework is clearly indicated. Depending on the goal, it can then be a consumption-based approach, i.e. the relation of the results to a person/household, or a product-centred approach, i.e. the relation to the service. Study goals, on the other hand, which focus on questions along the life cycle of ICT devices, i.e. on the environmental assessment of types of production, or disposal or focus on comparison with regard to the technical performance of devices, clearly indicate that higher-order effects should not be included.

The situation is less obvious for studies that address the environmental performance of ICT-based services as a whole. Horner et al., 2016, for example, show that differences in user behaviour can play an important role in determining the environmental performance of ICT-based services. This means that higher-order effects should also be included in cases where the environmental impacts of the application of ICT-based services are to be investigated (e.g. when determining net saving effects). This is equally true if conclusions are to be drawn about the environmental saving potential through substitution when comparing conventional applications with their digitalised counterparts. However, also in the case of the application of ICT-based services, it can also be a study goal to assess ICT-based services in terms of their technical performance, e.g. watching a movie from a streaming provider via different end-user devices. In this case, the inclusion of use-related higher-order effects would distort the analysis, as differences in the results could no longer be clearly attributed. In these cases, however, no conclusions can be drawn with regard to the environmental effects from the actual use of the service. In addition to the study goal, the intended use of the study results can therefore also be decisive in determining whether higher-order effects are to be included in the modelling.

4.3.2 Functional unit

The functional unit describes the "qualitative and quantitative aspects of the function(s)" (European Commission et al., 2010), and "should reflect reality well" (Reap et al., 2008). The definition of the functional unit is also dependent on the study goal and scope, e.g. whether a comparison of several processes or products is to take place, with regard to the geographical and temporal scope, or with regard to the intended use of LCA study results (European Commission et al., 2010). For studies aiming to investigate the environmental saving potential of an ICT-based service, or to capture different usage patterns, requirements for the definition of the functional unit could be identified based on the two case studies in this research, which allow the inclusion of variances in user behaviour (i.e. rebound effects and induction effects) in the modelling while ensuring functional comparability:

- Reference to the service provision instead of the product, thus allowing for different product characteristics to fulfil the services.
- Reference of the service provision to time, thus allowing the integration of intensification of use.

These criteria identified here are by no means specific to the inclusion of variances in user behaviour in the modelling, but should actually be part of good LCA modelling practice, in line with the recommendations in the International Reference Life Cycle Data System (ILCD) handbook (European Commission et al., 2010). Similar requirements for the definition of the functional unit to integrate variances in user behaviour into the environmental assessment of product-service systems (PSS) have also been proposed by Kjaer et al., 2016. Nevertheless, an analysis of several case studies that aimed at analysing the relevance of different usage patterns on the overall results in Publication 3 showed that not all functional unit definitions allowed for the inclusion of use-related higher-order effects such as intensification of use or use of more products. For example, functional unit definitions referred to the use of a specific amount of a product, e.g. "one shower event" (Shahmohammadi et al., 2019), rather than the use of a product over a defined time period, thereby excluding differences in use intensities. Other studies have referred to certain types of products in their definition of the functional unit, e.g. "a 2.5-kW rated inverter air-conditioning system" (Ross and Cheah, 2017), thus making it impossible to integrate changes with regard to product choices while ensuring functional comparability between products.

The latter two examples in particular illustrate the close link between the study goal and the definition of the functional unit. If, for example, the aim of the study was to compare different shower heads, the functional unit "one shower event" could be suitable. However, if the influence of different usage patterns on the environmental assessment is to be explicitly investigated, the appropriate choice of functional unit should ensure that different usage patterns can be integrated into the LCA model. However, a disadvantage of focusing on the service provision instead of a specific product when defining the functional unit is that it comes at the expense of defining the product to be investigated as precisely as possible. Reproducibility of study results (European Commission et al., 2010) and the informative value with regard to any impacts from the production phase is therefore limited. In addition, depending on the study goal, this may also mean that different products are no longer compared with each other. Instead, the product usage behaviour of individual consumers is compared over time in a consumption-based approach. This can have a decisive influence on any study outcomes.

Another issue related to the reference to the service provided arises with regard to the handling of multifunctionality. By including additional SHS components, other services can also be used, e.g. security, control or comfort. In the context of LCA methodology, this could therefore be considered a multifunctional product system, which poses a challenge to comparability and implies modifications of system boundaries (Reap et al., 2008).

Taking into account the study's primary research focus, the functional unit in the first case study in Publication 2 was defined as: *110 m2 apartment space in Germany managed (monitored and controlled) for 5 years*. Reference to the service provided allowed for inclusion of varying product characteristics, and the reference to a five year period of time allowed for capturing potential variances in user behaviour. Specification of the housing size was based on the average living space of the sample and period of time was based on the average life time of SHS devices assumed in previous studies. However, a disadvantage of this way of defining the functional unit is that any differences in technical performance due to different types of smart heating control devices are not included in the assessment. This can lead, among other things, to only a rough indication of the payback times determined within the scope of this study. In addition, the comparability between different household sizes was not considered in the definition of the functional unit in the first case study. As analysed in Publication 3, for smart heating control, the size of the living space is of central importance, as it determines the intensity of optimisation effects and rebound effects in absolute terms. For this reason, the living space was precisely defined in the functional unit, though this meant that a comparison with other household sizes is not feasible. In any case, this approach had no implications for carrying out the first case study, as no different SHS were examined there.

Accordingly, the definition of the functional unit was revised in the second case study in Publication 3 and, taking into account the study's modified research focus, was defined as: *Providing the service of energy management in a residence for one resident over the period of one year*. By adopting a consumption-based approach as suggested by Sala et al., 2019, it was taken into account that both the size of the living space and the number of residents in the household have an impact on the overall energy consumption. Thus, by referring to one resident rather than the entire household, a comparison within the sample of 375 SHS could be ensured. In addition, by referring to the service of energy management, it was ensured that differences in product characteristics could be included in the modelling. Reference to the time period of one year ensured that variances in use intensities can be included. It should be critically noted here, however, that the definition of the functional unit in the second case study was not entirely precise. Since only smart heating control was examined, it would have been more accurate to refer to it in the definition of the functional unit rather than to energy management in general.

However, this study's consumption-based approach also explicitly shifted the focus of the investigation away from comparing products (i.e. different SHS) to comparing different product use behaviours in the smart home. This was necessary in order to allow for the inclusion of the heating energy demands of different living conditions that accompany the use of a certain amount of floor space. That said, when variances in user behaviour are only investigated as a boundary condition, the definition of the functional unit could refer to a specific SHS composition. Sensitivity of the results in terms of varying user behaviour or differences in living sizes could be investigated using different scenarios.

4.3.3 Product system

A second modelling parameter that is closely related to the definition of the functional unit is the definition of the product system. A product system can be "any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analysed in the context of the LCA study" (European Commission et al., 2010). In order to enable integration of variances in product characteristics in the modelling (i.e. induction effects), the definition of the functional unit refers to the service provision instead of a specific product. This means that for the definition of the product system of ICT-based services, an umbrella term that encompasses all the different product characteristics is used. In both case studies, based on the online survey, the product system was therefore defined very generally as an *SHS that encompasses heating* to allow for the integration of variances in product characteristics with regard to SHS composition (type of components and number of devices). In this way, one of the main criticisms of previous SHS research is overcome, namely that only individual applications are considered and therefore large parts of the environmental impacts caused by other components of the SHS remain unaddressed (Dam et al., 2013; Nicholls et al., 2020).

This approach has implications for the modelling of production phase and End of Life (EoL) phase. As there is no clear assignment to a specific product type, only a rather general product model can be used and the actual processes during the production phase and the EoL phase are unclear. In both case studies of this thesis, a proxy device was used as a model for the SHS with rather conservative assumptions regarding the material composition, which means that the influence of the production phase and thus also the influence of the induction effect was overestimated. The EoL phase was not included in the life cycle in either case study, but, similar to the production phase, the more general the definition of the functional unit, the more generic the disposal paths of the product actually used. This modelling approach thus represents a potential source of uncertainty and is discussed in Subsection 4.2.

4.3.4 Multifunctionality

Multifunctionality is not only a challenge for LCA methodology in general (Moretti et al., 2020), but also specifically for the assessment of ICT-based services (Itten et al., 2020). According to ISO 14040, 2006 the usual approach to multifunctionality in LCA is either the subdivision of unit processes into sub-processes, or system expansion to include additional functions. If this is not feasible, allocation based on physical, economic, or other relationships can be used.

In both case studies, two subsectors of ICT hardware can be distinguished that are involved in the service provision and in which multifunctionality plays a role. For one, the ICT infrastructure involved in data transmission, processing and storage consists of many different ICT hardware devices (e.g. server, switches, cables) that are used by many users and for many purposes. The other is that the SHS components such as sensors or detectors can be used for the provision of several services.

With regard to the case studies of this research, in order to include induction effects in the SHS an approach is needed that allows for capturing variances in product characteristics in LCA. It is therefore argued that the extension of the SHS with new components should not be considered as an addition of new functionalities, but as different versions of the same overall product.

With regard to multifunctional end-user devices, depending on the study goal, both allocation and system expansion are applied in the literature. For example, considering using end-user devices for other purposes, studies on movie distribution (Hochschorner et al., 2015) or on e-paper newspapers (Moberg et al., 2010) applied allocation of the environmental impact from the life cycle of the end-user devices based on use-times. In contrast, in a comparative study of a smartphone, Judl et al., 2012 used several product systems as a reference system to ensure functional equivalence when comparing the multifunctional smartphone with alternative products. However, with regard to the inclusion of induction effects in the case studies subdivision or allocation is not an option, because these approaches would mean that only a sub-system of the product system is considered without the induced parts (i.e. the induction effect is excluded), as was done for example in the study by Moberg et al., 2010. However, it is also questionable whether the inclusion of induction effects in the LCA, as proposed here, can be described as system expansion in the sense of ISO 14040, 2006. Since this would mean that when comparing several SHS that do not consist of the same components, as is the case in the second case study, additional product systems would have to be added as a reference system to ensure functional equivalence, as was done, for example, by Judl et al., 2012. Thus, the importance of functional equivalence with regard to the product under assessment does not seem to fit when it comes to the inclusion of induction effects. This is further substantiated when research on the dynamics of ICT deployment in other sectors is taken into account (Frick and Matthies, 2020; Galvin, 2015; Røpke et al., 2010), showing that the introduction of ICT has created completely new applications, needs and material demands.

From this, however, the suitability of the LCA method for capturing induction effects could also be fundamentally questioned, as for example Kjaer et al., 2016 do for the issue of multifunctionality of PSS. However, according to the ILCD handbook, methodological flexibility is generally possible within the framework of LCA studies if the application requires it (European Commission et al., 2010). In addition, a rather similar proposition for dealing with multifunctionality has already been made, namely that equivalence of functions is determined by the users themselves (ISO/TR 14049, 2012). In that sense, the assignment of different components to the product system *SHS that encompasses heating* can be supported by the study design, as it was based on the online survey.

A similar approach has been developed by Kim et al., 2017, who propose to classify functionalities of multifunctional products according to basic feature, technical specifications and excitement features, with the basic feature being the defining element of the functional unit. However, as stated in the ILCD handbook (European Commission et al., 2010), methodological flexibility comes at the expense of strictness and reproducibility. In addition, the inclusion of induction effects in the LCA can lead to double counting when extrapolating the study results.

With regard to ICT infrastructure, in both case studies of this research, the environmental impact from ICT infrastructure was allocated based on data volumes over time in line with Schien and Preist, 2014. According to Coroamă and Hilty, 2014, this is the usual approach to the inclusion of ICT infrastructure in LCA models. However, similar modelling approaches arrive at different energy intensities in kwH/GB, as they assume different system boundaries and also make different assumptions (Schien and Preist, 2014), hence the impact of ICT infrastructure on the overall results of ICT-based services remains unclear.

Furthermore, this approach can be criticised in general because it assumes a proportional increase in energy consumption with increasing data volumes (Coroamă and Hilty, 2014), which, however, cannot be observed for the development of the overall energy consumption of the global data centre market (Masanet et al., 2020). Alternative allocation rules independent of the data volumes such as calculation per time unit (Coroamă and Hilty, 2014) or per subscriber (Lundén et al., 2022) are currently controversially debated, and future research into both appropriate methodology and inventory encompassing the whole life cycle is needed.

4.4 Transferability of the conceptual framework

The conceptual framework has so far only been applied to the case of smart homes in the context of this thesis. An examination of the applicability of the conceptual framework to ICT-based services in other consumption domains is still pending. However, from the additional publications of this thesis in which the conceptual framework has been applied in parts to the areas of media consumption (video streaming, Suski et al., 2020), and mobility (telework, Vaddadi et al., 2020), it can be concluded that a transfer to other application areas is generally possible. A helpful approach when applying the conceptual framework to other areas could be to first analyse the corresponding ICT-based services in terms of their environmental effects before assigning them to the user-driven parameters of the conceptual framework. Based on findings from recent literature studies on a range of ICT-based services in consumption domains such as mobility (Hook et al., 2020), digital goods (Court and Sorrell, 2020), or food and housing (Wilson et al., 2020) showing partly contradictory results and high dependency on user behaviour, it is expected that the application of the conceptual framework can provide new insights into the relevance of higher-order effects in these areas. However, this also depends on whether there is access to behavioural data. It would also be interesting to expand research on resource-efficient software to include aspects of user behaviour.

Also with regard to the environmental assessment of products and services without a digital component, adoption of the conceptual framework is pending. Similar to the environmental assessment of ICT-based services, variance in usage behaviour could be integrated into the LCA through the inclusion of the conceptual framework, if appropriate to the scope of the study. Similarly, depending on the study goal, the focus of LCA can also change from producer to consumer (Sala et al., 2019) with the product under investigation representing the interface between the two approaches.

To verify the transferabilty of the conceptual framework across disciplines, Figure 4 depicts the connection of the parameters from the framework to the environmental effects of ICT, and to those socio-technical parameters of product use (Gram-Hanssen, 2013) that influence the energy demand in the household, as well as to the different consumption phases (Geiger et al., 2018). Hence, for the area of consumer goods, the transferability of the conceptual framework is possible, as the comparison of the framework with the socio-technical parameters in the household shows. Findings from Moser and Kleinhückelkotten, 2018 suggest that variances in user behaviour could play a decisive role also in the consumption domains of mobility and food. However, whether it is possible to transfer and apply the conceptual framework to these domains depends on whether there are suitable frameworks for the operationalisation of the user-driven parameters. In product development, especially of transformative technologies, the inclusion of variances in user behaviour could provide valuable insights into the intended application for different user groups.

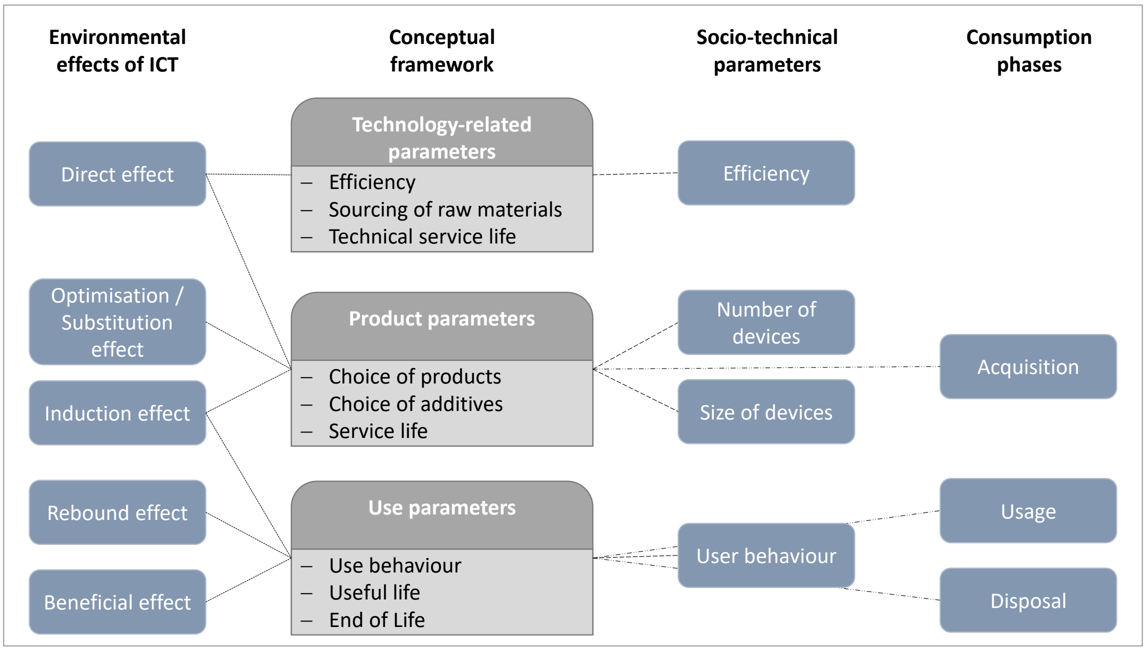

Figure 4: Connection of the conceptual framework presented in Publication 2 to environmental effects of ICT (Publication 1), socio-technical parameters of product use in the household (Gram-Hanssen, 2013) and consumption phases (Geiger et al., 2018).

With regard to the transferability of the framework to other life cycle phases such as production and EoL, it can be stated that the approach is complementary to the research already taking place which captures variances in production, e.g. through different suppliers, machinery and EoL. There are overlaps in cases where user behaviour plays a role, e.g. in relation to a specific disposal path that is determined or enabled by the user.

4.5 Future research

For research into the environmental effects of ICT, it can be deduced from the findings that the manifestation and operationalisation of ICT-induced rebound effects and induction effects should be advanced: Existing research on rebound effects of ICT (Frick and Matthies, 2020; Townsend and Coroamă, 2018), as well as of other consumption domains (see e.g. Buhl et al., 2017; Matiaske et al., 2012; Reimers et al., 2021) can be built upon. However, as discussed in Publication 1 and Publication 2, there is a lack of empirical data on potential levels of rebound effects in the different sectors. This is problematic because in order to harness the transformative potential of ICT, policy action is needed based on evidence about the causes and magnitude of rebound effects of ICT (Lange et al., 2020).

For induction effects, scientific debate on the causes, manifestation and relevance of induction effects of ICT is only just emerging. Overall, the role of induction effects for the environmental assessment of ICT-based services has hardly been investigated so far. More conceptual and empirical work is urgently needed here. As shown in Publication 2 and Publication 3 of this thesis, one possibility is to draw on a wide range of studies from consumer and behavioural research on the acquisition phase for future investigations.

The shifts in environmental impacts caused by the use of ICT-based services also need more attention. On the one hand, due to the introduction of ICT-based services, shifts in impacts may occur regarding impactful life cycle phases, e.g. a shift from the use phase to production phase as it is the case with the introduction of smart heating control, or a shift of operational energy demand from the user to the provider, as it is the case with video streaming (Shehabi et al., 2014). On the other hand, impact shifting due to the introduction of ICT-based services can take place between individual impact categories, as shown e.g. for smart homes and GWP/PED and MDP/ADP in Publication 2, and Publication 3. Significantly more case studies on impact shifting from the deployment of ICT-based services are needed, e.g. how the climate change mitigation potential of specific ICT applications relates to resource criticality, water consumption or land use. On the one hand, as part of good LCA practice, a comprehensive impact assessment should be conducted whenever possible. Meanwhile, well-founded findings on this are also urgently needed for the environmental regulation of the digital sector. This should go far beyond climate change mitigation, e.g. in current discourses on supply chain risks in Europe (Hanski et al., 2021), on the establishment of semiconductor production in Europe (Kleinhans, 2021) or on the regulation of digital platform markets (Staab et al., 2022).

Another crucial issue when integrating higher-order effects of ICT into the environmental assessment is data availability. The study design applied here also included the collection of primary data through an online survey. However, collection of primary data is usually time-consuming and costly. In addition to the necessary further development and application of combined environmental assessment and primary data collection, e.g. in Living Labs, more focused work should be done on building databases for behavioural data that can also be used for life cycle assessments. Horner et al., 2016 have already proposed this for energy use data for ICT hardware and ICT-based services. Bieser et al., 2022 show how databases on time-use can be used for the environmental assessment of ICT-based services. Other databases could include data on product acquisition, adoption rates of digital technologies, induced consumption effects and behavioural changes. As discussed in Section 4.2, it is crucial to ensure that data is representative.

Independently of the ICT use case, this research has highlighted that for questions relating to the use/application of products there is an urgent need to continue working on methodological approaches on how to integrate variances in user behaviour into the LCA. In particular for the inclusion of variances in product choices and induced consumption this research has highlighted that more research is needed, both with regard to the identification and manifestation of said effects and method development. From this research it can be derived that issues such as the handling of multifunctional products, integration of user perceptions with regard to the definition of product systems, or the definition of the functional unit play a certain role.

Finally, the second case study in Publication 3 provides initial ideas on how to take user characteristics into account in greater depth when interpreting results by using multiple regression analysis to investigate the linkages between environmental performance of SHS, sociodemographics and user motivation. The relation between the environmental assessment results of products and services, and the influence of user characteristics such as socio-economic factors or motivational factors is so far hardly discussed. Considering potential linkages might be important when deducing recommendations for policy and practice, for example by explaining the context of use, showing limits of scalability or defining specific target groups. The analysis conducted in the second case study is only a first attempt. It is recommended to further explore potential linkages in future research.

5 Conclusions

In this thesis the integration of higher-order environmental effects into LCA of ICT was investigated. Their inclusion in LCA of ICT is important when determining the overall net saving effects, as use-related higher-order effects in particular influence the realisation of the technical savings potential of ICT.

Accordingly, *RQ1* asked about the current challenges of including higher-order effects of ICT into LCA. To this end, LCA studies were reviewed to see how these were or were not included into the modelling. The analysis showed that user behaviour plays a central role when integrating higher-order effects of ICT-based services. However, due to methodological and data availability challenges, these are often insufficiently included into the modelling. It was found that the definition of goal and scope in an LCA is of particular importance in order to properly address those use-related higher-order effects in LCA. In addition, it was found that interdisciplinary approaches are required that combine a sound understanding of both user behaviour in specific contexts and LCA modelling. Based on the identified challenges, *RQ2* considered how higher-order effects can be properly addressed in the goal and scope definition in LCA. *RQ3* focused on the operationalisation of the conceptual framework and its application to the case of smart homes.

The conceptual framework *The user perspective in LCA* distinguished between product parameters and use parameters, which describe usage behaviour in relation to the choice of products, and in relation to the usage behaviour of the products. Both categories were grouped under the term "user-driven parameters" to distinguish them from "producer-driven parameters", which provide information such as the efficiency of the technology or the sourcing of raw materials. Socio-demographic information on the user constitutes another category. Relevant LCA modelling characteristics were assigned to the categories of product parameters, use parameters and sociodemographic information to make them applicable to LCA. The definition of the functional unit was identified as particularly relevant for the integration of higher-order effects into the goal and scope definition.

The conceptual framework was applied to the case of smart homes with smart heating. The study design included the operationalisation of the user-driven parameters and the collection of primary data through an online survey as well as the environmental assessment of the average SHS in Germany (first case study) and of 375 different SHS in Germany (second case study). In a last step, the assessment results were analysed with regard to the minimum energy saving requirements of an SHS (first case study), and variances in user behaviour (second case study).

Results of the first case study show that optimisation effects in the average smart home must be at least 6% of annual heating energy demand over three years in order to balance out the effects of the production and operation of the SHS for GWP and PED. In the second case study, large differences in the environmental performance for the different SHS were found. With regard to the role of user behaviour for the environmental assessment of an SHS, it was found that both choice of SHS devices and actual heating behaviour have a decisive influence on the overall environmental performance of the SHS. Choice of SHS devices (i.e. the induction effect) is particularly relevant and accounts for a large part of the environmental effects of production and operation of the SHS in both case studies, and for all impact categories considered. With regard to variances in heating behaviour (i.e. rebound effects), on average no significant difference in heating behaviour can be observed in both studies. However, there are large differences within the sample, which lead to considerable changes in the environmental performance of individual SHS for certain impact categories in some cases. This emphasises that user behaviour can play an important role in both increasing or decreasing heating energy consumption in the smart home, and that it should therefore be considered. Considering user behaviour, the findings also underline the need for sufficient validation of user behaviour data, e.g. by choosing appropriate data collection method, or by ensuring representativeness of the respective reference group.

The overall contribution of this research is threefold: First, a conceptual framework was developed allowing for the integration of higher-order effects of ICT in LCA modelling. Second, from the application in an interdisciplinary study design, three factors were idenified that are decisive when integrating higher-order effects into LCA of ICT. Third, valuable insights into the environmental effects of smart homes with smart heating in Germany were provided. The relevance of induction effects for achieving net savings was particularly well demonstrated.

The findings of this research should be considered when planning future research. For example, it is necessary to investigate environmental effects of ICT-based services in other application areas. In these contexts, the conceptual framework could be a valuable tool for integrating use-driven higher-order effects into the modelling. To address the lack of data on user behaviour, further interdisciplinary approaches combining environmental assessments and primary data collection should also be explored. Finally, extending interdisciplinary approaches to investigate links between environmental assessments and sociodemographic information or user motivation should clearly be further explored. In this way, environmental assessment results could be characterised more precisely, for example with regard to specific user groups. This could make results more transferable, for example, for scaling, for the development of policy measures or for the ecodesign of products.

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Appendix

The appendix contains supplementary material to Publication 2 (Pohl et al., 2021), and Publication 3 (Pohl et al., 2022).

Supplementary material to Publication 2

Pohl, J., Frick, V., Höfner, A., Santarius, T., Finkbeiner, M., 2021. Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home? Journal of Cleaner Production 312, 127845. https://doi.org/10.1016/j.jclepro.2021.127845

- **Supplementary material A** contains information on the composition of the average smart home system (SHS) in Germany based on the survey.
- **Supplementary material B** contains information on the modelling of the smart home system, i.e. on the composition of the proxy device, and on inputs for life cycle inventory for the different energy use models.
- **Supplementary material C** provides detailed results for the different saving scenarios for PED, GWP, ADP and Ecotox, and results of sensitivity analyses for PED, GWP, ADP and Ecotox.

Supplementary material A to the article "Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home?"
(Journal of Cleaner Production)

Johanna Pohl, Vivian Frick, Anja Hoefner, Tilman Santarius and Matthias Finkbeiner

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Supplementary material A contains information on the composition of the average smart home system (SHS) in Germany based on the survey.

Table A1 Devices (coverage and number) of the average SHS based on the online survey and related technical data (weight, load)

Component	Coverage [.]	No. of devices	Weight/ device [kg]	Load [W]			Reference
				WiFi[1]	other RF[1]	Stand by[2]	
Radiator thermostat	1	3.97	0.14	1.77	1.77	1	Bosch: Thermostat AA
Humidity sensor	0.35	2.4	0.045	1.2	0.001	0.6	ABUS: Z-Wave Wassermelder
Door/window sensor	0.34	4.16	0.04	1.2	0.001	0.6	Bosch: Contact AA
Motion sensor	0.43	2.52	0.098	1.2	0.001	0.6	Bosch: Motion Detector
(Security) Camera	0.37	1.92	0.45	2	2	2[3]	Bosch: 360° Indoor Camera
Smoke detector	0.46	3.64	0.165	1.2	0.001	0.6	Bosch: Smoke Detector
Wireless intercom system	0.33	1.18	0.237	2	2	2[3]	Ring: Video Doorbell 2
Smart plug	0.49	2.84	0.155	1.2	0.001	0.6	Bosch: Smart Plug AA
Switch	0.30	1.63	0.063	1.2	0.001	0.6	Bosch: Universal Switch Flex
Control unit	0.73	1.1	0.19	6	6	/[4]	Bosch: Smart Home Controller

[1] according to IEA 4E (2019, p. 53)

[2] according to Friedli et al. (2016, p. 5)

[3] no differences assumed, as data is inconsistent

[4] 24h/day Network Active

Table A2 Smart home infrastructure in the average smart home according to the sample

Communication network	Coverage [%]	Control and management devices	Coverage [%]
WiFi	0.79	Mobile device (Smartphone/Tablet)	0.8
Other RF standards	0.35	Central HUB/ Gateway	0.38
Bluetooth	0.24	Computer/Laptop	0.32
Wired	0.14	Voice command device	0.25
Don't know	0.04	Don't know	0.01

Table A3 Average room temperature of smart home group and control group according to the sample in line with Kleinhückelkotten (2016)

Heating behaviour	**Smart home with smart heating system**	**Control group**
	N = 375	N = 399
Average room temperature M	19.43 °C	19.45 °C

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Supplementary material B to the article "Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home?"
(Journal of Cleaner Production)

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Supplementary material B contains information on the modelling of the smart home system, i.e. on the composition of the proxy device, and on inputs for life cycle inventory for the different energy use models.

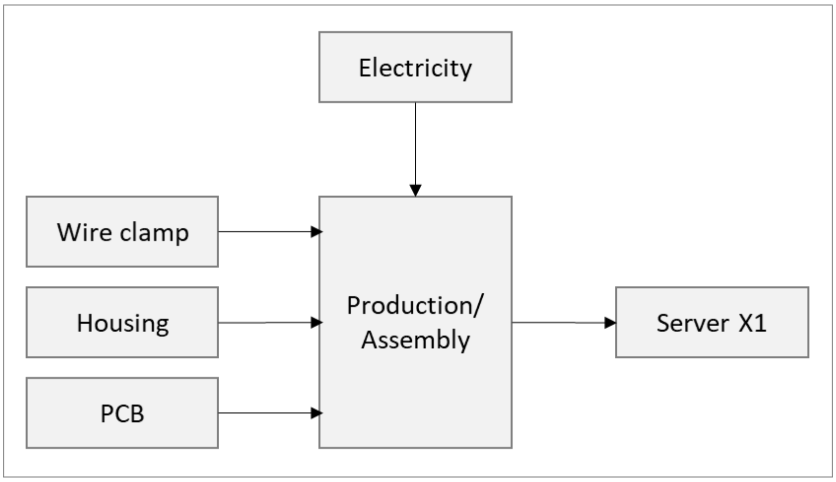

Fig. B1 Composition proxy device Gira X1

Table B1 Composition proxy device and reference data sets in GaBi

Component	Weight-based share	Reference data sets
Wire clamp	0.032	GLO: electric connector, wire clamp (ecoinvent)
Housing	0.431	DE: Polymethylmethacrylate granulate (PMMA) mix (Gabi) DE: Polycarbonate Granulate (PC) (GaBi) DE: Polyethylene High Density Granulate (HDPE/PE-HD) Mix (GaBi)
Populated Circuit Board (PCB)	0.536	GLO: printed wiring board, mounted mainboard, laptop computer, Pb free (ecoinvent)
Electricity	.	DE: Electricity grid mix ts (GaBi); for downstream energy use EU-28 electricity grid mix (GaBi); for upstream energy use

Table B2 Upstream energy use: energy intensity of data transmission

ICT infrastructure	Energy intensity of data transmission [kWh/GB]	Reference year	Reference
Home and access network	0.004	2014	(Krug et al. 2014)
Core and edge network	0.02	2014	(Schien and Preist 2014)
Data center	0.015	2020	(Andrae 2019)

Table B3 Heating energy use: heating energy sources and reference heating appliances in GaBi

Heating energy source	[Share Sample]	[Share w/o Electricity][1]	Reference heating appliances	
			1 - 2 family home (share of 61.6%)	Apartment building (share of 38.4%)
Gas	58.9	66.2	Gas low temperature boiler < 20 kW (EN15804 B6)	Gas low temperature boiler 20-120 kW (EN15804 B6)
Oil	19.2	21.5	Oil low temperature < 20 kW (EN15804 B6)	Oil low temperature boiler 20-120 kW (EN15804 B6)
Coal[2]	1.3	1.5	Europe without Switzerland: heat production, hard coal briquette, stove 5-15kW ecoinvent 3.5	
Wood	2.5	2.8	Pellet boiler < 20 kW (EN15804 B6)	Pellet boiler 20-120 kW (EN15804 B6)
Other[3] (District Heating)	7.1	8	District heating 20-120 kW (EN15804 B6)	
Electricity	11.0		excluded[1]	excluded[1]

[1] Electricity was excluded as heating energy source, as no clear reference heating appliance could be assigned.

[2] The share of coal was taken from German heating energy statistics (AGEB 2019), as only the share of solid heating energy source (coal and biomass) was known.

[3] "Other" heating energy sources was interpreted as 100% district heating. Theoretically, other heating energy sources and appliances are possible.

Table B4 Energy Saving Scenarios SHS over time

t(a)	Saving Scenario 2% [kWh]	Saving Scenario 4% [kWh]	Saving Scenario 6% [kWh]	Saving Scenario 10% [kWh]	Saving Scenario 20% [kWh]
0	0	0	0	0	0
1	296.23	592.46	888.69	1481.15	2962.3
2	592.46	1184.92	1777.38	2962.3	5924.6
3	888.69	1777.38	2666.07	4443.45	8886.9
4	1184.92	2369.84	3554.76	5924.6	11849.2
5	1481.15	2962.3	4443.45	7405.75	14811.5
6	1777.38	3554.76	5332.14	8886.9	17773.8
7	2073.61	4147.22	6220.83	10368.05	20736.1
8	2369.84	4739.68	7109.52	11849.2	23698.4
9	2666.07	5332.14	7998.21	13330.35	26660.7
10	2962.3	5924.6	8886.9	14811.5	29623

Table B5 Green Energy Mix (UBA 2017)

Energy Source	Share [.]	GaBi Reference data set
Wind power	0.41	DE: Electricity from wind power
Photovoltaic	0.20	DE: Electricity from photovoltaic
Hydro power	0.11	DE: Electricity from hydro power
Biomass - gas	0.18	DE: Electricity from biogas
Biomass - solid	0.06	DE: Electricity from biomass (solid)
Biomass - waste	0.03	DE: Electricity from waste

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Supplementary material C to the article “Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home?”
(Journal of Cleaner Production)

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Supplementary material C provides detailed results for the different saving scenarios for PED, GWP, ADP and Ecotox, and results of sensitivity analyses for PED, GWP, ADP and Ecotox.

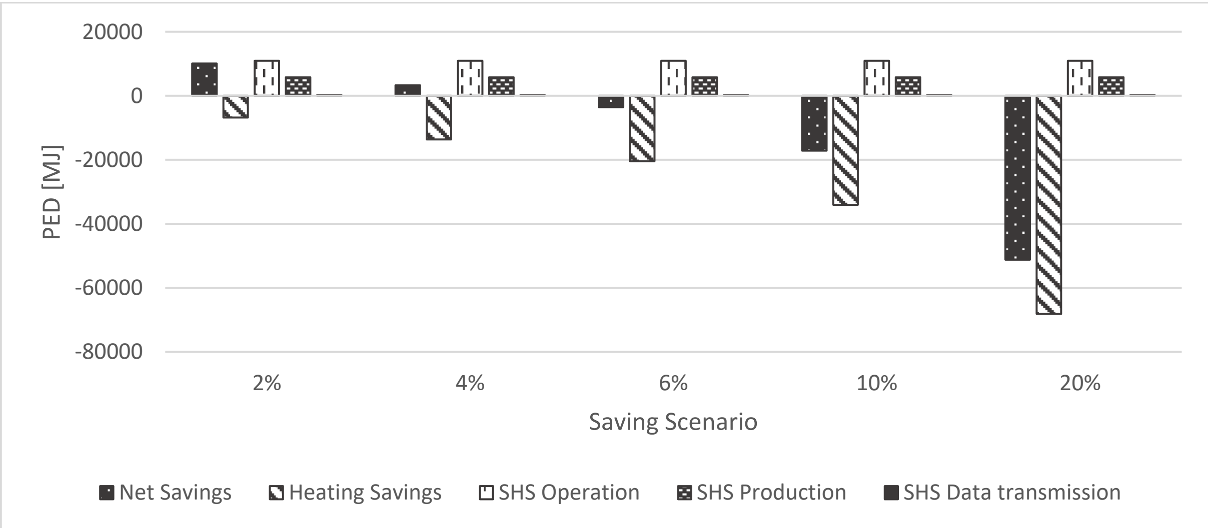

Fig C1 Changes in impact category PED of the Smart Home System for 5 scenarios and lifetime of 5 years

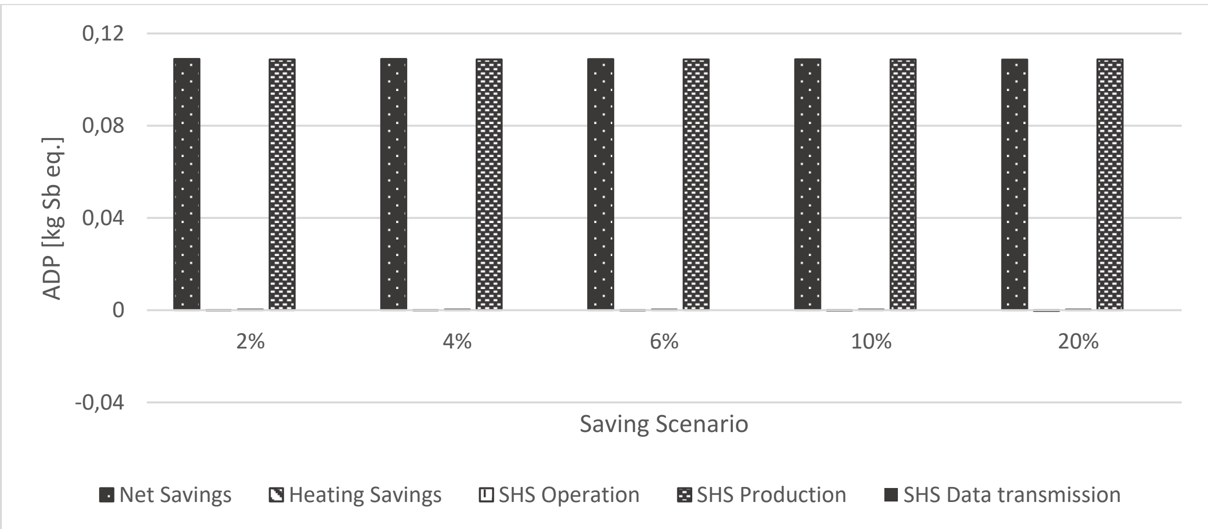

Fig C2 Changes in impact category ADP of the Smart Home System for 5 scenarios and lifetime of 5 years

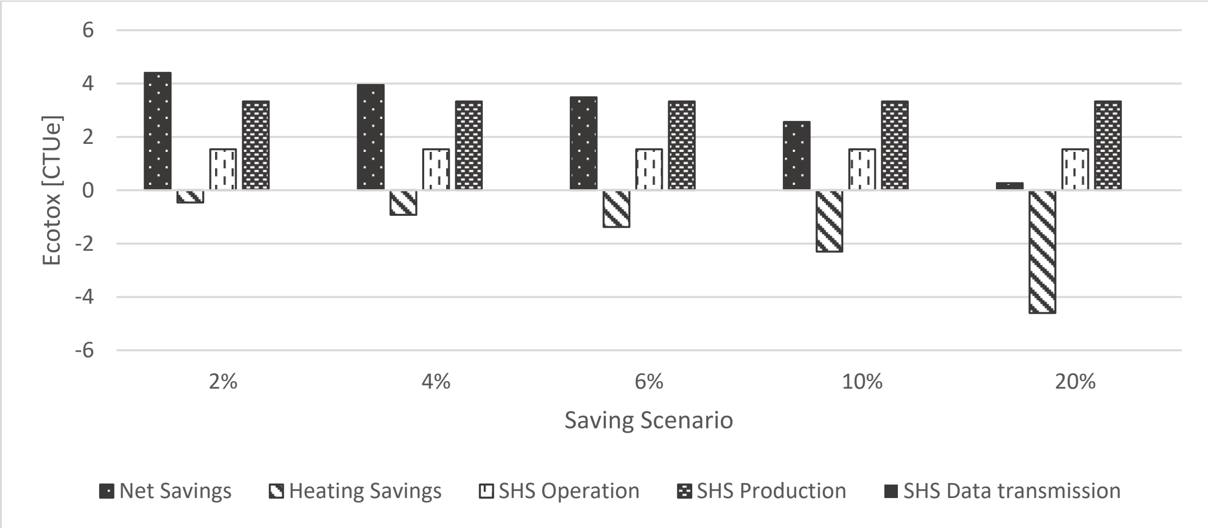

Fig C3 Changes in impact category Ecotox of the Smart Home System for 5 scenarios and lifetime of 5 years

Table C1 Net saving effects, break-even point and payback time for PED, GWP, ADP and Ecotox

Saving Scenario		**2%**	**4%**	**6%**	**10%**	**20%**
Net savings over 5 years	*PED [MJ]*	/	/	3,533	17,160	51,228
	GWP [kg CO2 eq.]	/	/	381	1,250	3,423
	ADP [kg Sb eq.]	/	/	/	/	/
	Ecotox [CTUe]	/	/	/	/	/
Net savings over 10 years	*PED [MJ]*	/	/	12,852	40,106	108,241
	GWP [kg CO_2 eq.]	/	244	1,113	2,851	7,196
	ADP [kg Sb eq.]	/	/	/	/	/
	Ecotox [CTUe]	/	/	/	/	2.8
Break-even point (life time 5 years)	*PED [MJ]*	/	/	12,691	8,590	6,914
	GWP [kg CO2 eq.]	/	/	625	476	404
	ADP [kg Sb eq.]	/	/	/	/	/
	Ecotox [CTUe]	/	/	/	/	/
Payback time [years]	*PED*	/	11.5*	3.1	1.3	0.5
	GWP	/	5.9*	2.4	1.1	0.5
	ADP	/	/	/	/	6,073.6*
	Ecotox	/	/	/	21.7*	5.4*

* payback time is not within the system's life time; / no net savings are achieved

Table C2 Payback time (years) for different operational energy settings for PED, GWP, ADP and Ecotox

Saving Scenario		**2%**	**4%**	**6%**	**10%**	**20%**
Operational energy demand incl. standby settings	*PED*	43.0*	3.9	2	1	0.5
	GWP	14.8*	3.2	1.8	0.9	0.4
	ADP	/	/	/	17878*	2837.7*
	Ecotox	/	282.2*	32.1*	11.6*	4.5
Operational energy demand - other RF	*PED*	/	4.3	2.1	1.1	0.5
	GWP	22.2*	3.4	1.8	1	0.4
	ADP	/	/	/	37,482.7*	3,094.6*
	Ecotox	/	/	40.2*	12.5*	4.6
Operational energy demand - Green Energy Grid Mix	*PED*	/	34.9*	3.8	1.4	0.5
	GWP	4.1	2	1.3	0.8	0.4
	ADP	/	/	/	/	/
	Ecotox	/	/	/	/	/
Operational energy demand - Future grid mix 2030	*PED*	/	10.3*	3	1.2	0.5
	GWP	/	4.7	2.2	1	0.5
	ADP	/	/	/	/	/
	Ecotox	/	/	/	18.8*	5.2*

* payback time is not within the system's life time

Supplementary material to Publication 3

Pohl, J., Frick, V., Finkbeiner, M., Santarius, T., 2022. Assessing the environmental performance of ICT-based services: Does user behaviour make all the difference? Sustainable Production and Consumption 31, 828–838. https://doi.org/10.1016/j.spc.2022.04.003

- **Supplementary material 1** contains a summary of LCA studies which investigate the interplay of user behaviour and environmental assessment of products and services (Table S1), as well as detailed results of SHS composition (Table S2), and environmental impact for GWP and MDP (Table S3).
- **Supplementary material 2** contains the online survey.

Supplementary material to the article "Assessing the environmental performance of ICT-based services: does user behaviour make all the difference?" (Journal Sustainable Production and Consumption)

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Supplementary material contains a summary of LCA studies which investigate the interplay of user behaviour and environmental assessment of products and services (Table S1), as well as detailed results of SHS composition (Table S2), and environmental impact for GWP and MDP (Table S3).

Tab S1: Summary of LCA studies which investigate the interplay of user behaviour and environmental assessment of products and services

Study	**Product interaction**	**Functional unit**	**Product system**	**Information on user behaviour**
Achachlouei and Moberg (2015)	Duration	One reader's use of one copy of Sköna Hem	print edition of a magazine and electronic edition read on a tablet device	No additional data; assumption on average use, sensitivity analysis for relevance
Amasawa et al. (2018)	Choice of products, duration	book reading activities per person and per person-book	books (both paper and e-book) purchased or acquired, and electronic device to read e-books	Primary data; information on reading patterns through a web survey in the USA and a 3-month social experiment involving e-readers in the USA to observe the changes in reading patterns upon e-reader adoption within the same population
Bossek et al. (2021)	Choice of products, duration, frequency of use	Reporting unit instead of FU "life of Dirk"	Human being	Primary data: collection of all the products and possessions consumed by the person up to the present time, and additional information on user behaviour, e.g. average life span or user ratio
O'Brien et al. (2009)	Frequency of use	Not clearly stated; only time period was specified: "environmental indicators of nappy system over the first 2.5 years of a child's life"	Two types of nappies: disposable/ reusable	No additional data; categorization of user behaviour (frequency of nappy changing) based on assumptions

Pohl et al. (2021)	Choice of products, duration, frequency of use	110 m^2 apartment space in Germany managed (monitored and controlled) for 5 years	typical SHS that encompasses heating in Germany	Primary data; information on the average SHS in Germany (components, number of devices, heating behaviour) and information on housing from a survey among 375 SHS users in Germany
Ross and Cheah (2017)	Choice of product setting, duration	lifetime of a 2.5-kW rated inverter air-conditioning system used to cool a single office	2.5-kW rated inverter air-conditioning system	Primary data; Inclusion of variances in air conditioning usage patterns in offices by measuring and analysing data such as room temperature, humidity or noise over a period of 5 months; data were collected using integrated sensor units
Samaras and Meisterling (2008)	Duration	1 km of vehicle travel in the United States.	Five types of vehicles: conventional vehicle with internal combustion, hybrid electric vehicle, 3 different plug-in hybrids	Partly primary data; assumption on frequency of charging, survey on driving distances
Schien et al. (2021)	Choice of products, duration, frequency of use	delivery and viewing of one year's worth of BBC television to the population of the UK	Viewing devices (e.g. mobile device, Smart TV), Internet and broadcast distribution	Primary data; survey data from broadcast provider on viewing behaviour
Shahmohammadi et al. (2017)	Choice of products, duration	One wash cycle	doing laundry including use of detergents and electricity consumption of washing machine (depending on load size, wash duration, temperature profile, efficiency)	Secondary data; regionally disaggregated data for 23 European countries, such as product related environmental data, data on background electricity mixes as well as data from a European consumer survey on product usage and washing habits.
Shahmohammadi et al. (2019)	Choice of products, duration	one shower event	Showering including water consumption (depending on duration and water flow rate) and electricity consumption (depending on type of water heater) and number, type and dosage of shower products, e.g. gel, shampoo, hair conditioner	Secondary data; User behaviour based on measured data from other research
Solli et al. (2009)	Product handling	1 kWh of heat delivered in a household	Two types of wood stoves	Secondary data; assumptions on user behaviour based on previous research

Tab. S2: Description of the SHS composition per resident, number of devices (mean, standard deviation, maximal & minimal number, share of newly purchased devices per component)

Component	**M**	**SD**	**MAX**	**MIN**	**Share newly purchased devices**
Radiator thermostat	2.405	1.445	7	0.345	0.816
Humidity sensor	0.838	1.453	7	0	0.824
Door/window sensor	0.508	0.936	7	0	0.848
Motion sensor	0.635	0.945	6	0	0.798
(Security) Camera	0.399	0.656	4	0	0.847
Smoke detector	0.929	1.282	7	0	0.721
Wireless intercom system	0.217	0.372	3.5	0	0.697
Smart plug	0.819	1.207	7	0	0.792
Switch	0.282	0.609	5	0	0.779
Control unit	0.487	0.383	2.667	0	0.858
SHS total	7.519	5.271	34	0.4	0.811

Tab S3: Split - environmental performance SHS on average

	GWP [kg CO2 eq per capita]				**MDP [kg CU eq per capita]**			
	MEAN	**SD**	**MIN**	**MAX**	**MEAN**	**SD**	**MIN**	**MAX**
Overall environmental impact	-35.1	239,9	-991.4	804.0	0.97	0.8	-0.1	4.79
Smart heating component	41.9	23.5	2.6	150.8	0.43	0.3	0.005	1.41
Other components	37.8	41.0	0	249.3	0.57	0.7	0	3.78
Optimisation effect	-103.9	42.9	-332.4	-6.7	-0.03	0.03	0.21	-0.004
Heating behaviour	-10.9	236.5	-870.6	877.8	-0.001	0.09	-0.74	0.5

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Supplementary material to the article "Assessing the environmental performance of ICT-based services: does user behaviour make all the difference?" (Journal Sustainable Production and Consumption)

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Online survey – smart home users

1. **Do you have a smart heating system?**
   By smart heating system we mean a heating control that is connected to other sensors, can be controlled externally or is self-learning.

☐ yes, I have a smart heating system → *continue with question 2*
☐ no, I do not have a smart heating control → *exclusion*

2. **Why do you use your smart home system?** *open question*
   Please tell us in keywords what you like about your smart home system or what you use it for.

3. **Why do you use your smart home system?** *table*
   I use my smart home system because....

	1 Strongly disagree	2	3	4	5 Strongly agree	6 Do not know
… I want to increase my security at home.	☐	☐	☐	☐	☐	☐
… I always want to be sure that my home is well secured.	☐	☐	☐	☐	☐	☐
… I can check that everything is safe at home while I'm away.	☐	☐	☐	☐	☐	☐
… because I want to meet my friends' expectations.	☐	☐	☐	☐	☐	☐
… because people who are important to me like smart homes.	☐	☐	☐	☐	☐	☐
… it arouses the interest of my acquaintances and friends.	☐	☐	☐	☐	☐	☐
.. it is a new experience.	☐	☐	☐	☐	☐	☐
… it is exciting.	☐	☐	☐	☐	☐	☐
… because I do not get bored with it.	☐	☐	☐	☐	☐	☐
… it automates tedious activities.	☐	☐	☐	☐	☐	☐
… it makes my life easier.	☐	☐	☐	☐	☐	☐
… it enables a high level of comfort.	☐	☐	☐	☐	☐	☐
… it works well for watching movies or listening to music.	☐	☐	☐	☐	☐	☐
…it allows me to place orders online.	☐	☐	☐	☐	☐	☐
… it enables me to use entertainment services throughout the whole flat.	☐	☐	☐	☐	☐	☐

… I like to be up to date with technology.	☐	☐	☐	☐	☐	☐
… I enjoy controlling a smart system.	☐	☐	☐	☐	☐	☐
... I like dealing with technical devices.	☐	☐	☐	☐	☐	☐
… it is an investment that pays off financially.	☐	☐	☐	☐	☐	☐
… it reduces my operating costs.	☐	☐	☐	☐	☐	☐
… it saves me money.	☐	☐	☐	☐	☐	☐
… it enables me to save resources.	☐	☐	☐	☐	☐	☐
… because it enables me to adjust my energy consumption so that I can live as environmentally friendly as possible.	☐	☐	☐	☐	☐	☐
… it helps me to protect the environment.	☐	☐	☐	☐	☐	☐
… it is of high and consistent quality.	☐	☐	☐	☐	☐	☐
… it is manufactured to a high standard.	☐	☐	☐	☐	☐	☐
… it meets the highest standards and expectations.	☐	☐	☐	☐	☐	☐

4. Who arranged for the smart heating system to be installed in your home?

☐ the landlord before I moved in
☐ the landlord after I moved in
☐ me when I moved in
☐ someone from my household when moving in
☐ me after I moved in
☐ someone from my household after moving in
☐ I do not know
(Multiple answers possible))

5. Since when do you have your smart heating system?
MM/YYYY

6. How important were the following reasons for you to acquire a smart home system?

	1 Not important	2	3	4	5 Very important	6 Do not know
Ensuring safety at home.	☐	☐	☐	☐	☐	☐
Increased comfort.	☐	☐	☐	☐	☐	☐
Possibility of controlling devices/my household.	☐	☐	☐	☐	☐	☐
Opportunity to protect the environment.	☐	☐	☐	☐	☐	☐
Saving money.	☐	☐	☐	☐	☐	☐
Expectations/interest of my friends/acquaintances/family.	☐	☐	☐	☐	☐	☐
That it was an exciting new acquisition.	☐	☐	☐	☐	☐	☐

Quality of the product.	☐	☐	☐	☐	☐	☐
My technology enthusiasm.	☐	☐	☐	☐	☐	☐

7. Please indicate to what extent you have noticed the following changes since you acquired your smart home system. Since using my smart home system...

	1 Strongly disagree	2	3	4	5 Strongly agree	7 Do not know
… I save time.	☐	☐	☐	☐	☐	☐
… I save money.	☐	☐	☐	☐	☐	☐
… I save energy.	☐	☐	☐	☐	☐	☐
… I save effort and hassle.	☐	☐	☐	☐	☐	☐

8. Since I started using my smart home system, …

The room temperature is lower than before.	☐	☐	☐	The room temperature is higher than before.
I heat fewer rooms than before	☐	☐	☐	I heat more rooms than before

9. Please indicate how often you do the following activities now compared to before you acquired your smart home.

	1 Much less than before	2	3 Same as before	4	5 Much more than before	6 Do not know
Listen to music	☐	☐	☐	☐	☐	☐
Watch TV / Movies	☐	☐	☐	☐	☐	☐
Buy electronic devices	☐	☐	☐	☐	☐	☐
Save energy by controlling my electricity consumption	☐	☐	☐	☐	☐	☐
Have lights switched on in rooms where I am not currently staying	☐	☐	☐	☐	☐	☐

10. Please indicate how often you perform the following activities. Please select "does not concern me" if you do not own a device.

	1 Never	2	3	4	5	6 Always	7 Does not concern me
I leave the TV on even if no one is watching.	☐	☐	☐	☐	☐	☐	☐
When I leave the room, I keep the light on.	☐	☐	☐	☐	☐	☐	☐

When buying new electrical devices, I consciously pay attention to their power consumption.	☐	☐	☐	☐	☐	☐	☐
I leave my devices in standby mode.	☐	☐	☐	☐	☐	☐	☐
In winter I ventilate only briefly, but intensively.	☐	☐	☐	☐	☐	☐	☐
I defrost my fridge.	☐	☐	☐	☐	☐	☐	☐
When using the washing machine, I wait until it is fully loaded.	☐	☐	☐	☐	☐	☐	☐
I turn the heating down or off before I go on holiday.	☐	☐	☐	☐	☐	☐	☐
I wash my clothes at a low temperature (hot clothes at 60°, only slightly dirty ones at 30°).	☐	☐	☐	☐	☐	☐	☐

11. [Environmental awareness] **How much do you agree with the following statements?**

	1 Strongly disagree	2	3	4 Strongly agree	5 Do not know
Environmental protection should be a priority for Germany, even if it compromises economic growth.	☐	☐	☐	☐	☐
Each and every one of us must take responsibility today in our own surroundings for preserving an environment worth living in for future generations.	☐	☐	☐	☐	☐
In order to preserve our natural livelihoods, we must all be willing to limit our standard of living.	☐	☐	☐	☐	☐
Through our way of life, we are also responsible for many environmental problems in other countries (e.g., through the exploitation of raw materials or waste exports).	☐	☐	☐	☐	☐
When buying, I pay attention to the sustainability of products (e.g. environmental compatibility, durability, fair working conditions).	☐	☐	☐	☐	☐

12. [Norm-Activation-Model] **Please indicate to what extent you agree with the following statements**.

	1 Strongly disagree	2	3	4	5 Strongly agree	6 Do not know
The electricity consumption of private households contributes significantly to the threat to natural environment.	☐	☐	☐	☐	☐	☐
The electricity consumption of Private households is a major contributor to climate change.	☐	☐	☐	☐	☐	☐
Rising electricity consumption in the private sector is a serious problem for the environment.	☐	☐	☐	☐	☐	☐
I am aware that my private energy saving behaviour has an impact on climate change.	☐	☐	☐	☐	☐	☐
I believe that through energy-saving behaviour I can make a contribution to protect the environment.	☐	☐	☐	☐	☐	☐
By consistently saving energy in the household, I can make a decisive contribution to environmental protection.	☐	☐	☐	☐	☐	☐
For environmental reasons, I personally feel obliged to generally save electricity in my household.	☐	☐	☐	☐	☐	☐
I personally consider it my duty to save energy in my household.	☐	☐	☐	☐	☐	☐
For environmental reasons, I personally feel obliged to save energy wherever possible.	☐	☐	☐	☐	☐	☐

13. [Green Tech Optimism] **Please indicate to what extent you agree with the following statements.**

	1 Strongly disagree	2	3	4	5 Strongly agree	6 Do not know
Seeing how the development of green technologies is progressing makes me optimistic about the situation of our environment.	☐	☐	☐	☐	☐	☐
Even through the further development of green technologies, we will not be able to stop climate change.	☐	☐	☐	☐	☐	☐
By using more and more efficient household appliances (refrigerator, washing machine, etc.) we can master climate problems.	☐	☐	☐	☐	☐	☐
The environmental problem will become less important as appliances	☐	☐	☐	☐	☐	☐

for household and everyday use require less and less energy.							

14. Do you have the following electronic devices in your household?

Devices	**Yes**	**No**	**Do not know**
Wall and radiator thermostats	☐	☐	☐
Window sensors	☐	☐	☐
Humidity and water sensors/humidity meters	☐	☐	☐
Door and window contacts (for ventilation)	☐	☐	☐
Motion detector	☐	☐	☐
Surveillance camera	☐	☐	☐
Fire alarm	☐	☐	☐
Door intercom/communication with video and Wi-Fi	☐	☐	☐
Washing machine	☐	☐	☐
Tumble dryer	☐	☐	☐
Robot hoover	☐	☐	☐
Refrigerator (also as freezer and refrigerator combination)	☐	☐	☐
Coffee machine	☐	☐	☐
Wi-Fi sockets	☐	☐	☐
Central switch for all sockets and lights	☐	☐	☐
TV	☐	☐	☐
DVD and Blu-ray devices	☐	☐	☐
Bluetooth-Multiroom-Soundsystem	☐	☐	☐
Speakers with voice control (e.g. Amazon Echo or Google Home)	☐	☐	☐
Stationary computer	☐	☐	☐
Laptop/Notebook/Netbook	☐	☐	☐
Tablet	☐	☐	☐
Printer	☐	☐	☐
Landline telephone	☐	☐	☐
Mobile phone (except smartphone)	☐	☐	☐
Smartphone	☐	☐	☐
Digital camera	☐	☐	☐
MP3 player	☐	☐	☐
Gaming console (also portable)	☐	☐	☐
Smart Watch	☐	☐	☐
Electronic body scale	☐	☐	☐
Smart thermometer	☐	☐	☐
Smart Home Central (control unit)	☐	☐	☐

15. How many of these devices do you own? *(Filter)*

Device	**1**	**2**	**3**	**4**	**5**	**6**	**7 or more**
[Filtered devices from No. 14]	☐	☐	☐	☐	☐	☐	☐

16. How many of the devices you own are interconnected? *(Filter)*

By interconnected, we mean that the devices are electronically connected to each other, e.g., by Wi-Fi or radio, and can exchange information. This way, the smart home system can e.g., be controlled via an app.

Device	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**All**	**Do not know**
[Filtered devices from No. 14]	☐	☐	☐	☐	☐	☐	☐	☐	☐

17. Please state for each of your devices whether… *(Filter)*

1) most of them already existed before you *set up* your *smart heating system* (e.g. you may have had a smartphone before owning a smart home system and are now also using it for it).
2) they were mainly *newly* purchased after the *smart heating system* was already set up.
3) they have predominantly replaced other devices that were not compatible with the smart home system.

Device	Already existed	Mainly newly purchased	Predominantly replaced other devices
[Filtered devices from No. 14]	☐	☐	☐

18. Please indicate which areas of your smart home system you use the most. *(Multiple answers possible)*

☐ Heating/Ventilation/Shading
☐ Multimedia/Entertainment (smart TV, voice-controlled speaker, smartphone/landline phone, etc.)
☐ Security functions (e.g., surveillance camera, door contacts etc.)
☐ Household appliances (e.g. hoover robots, connectable lamps, etc.)
☐ Gadgets (smart scale, smartwatch, etc.)
☐ Other, namely: *[free entry]*

19. How are your smart devices connected to *each other*? Please indicate all communication channels used. *[Multiple answers possible]*

☐ via radio connection
☐ via cables
☐ via bluetooth
☐ via Wi-Fi
☐ I do not know
☐ Other, namely: *[free entry]*

20. How do you *control* your smart devices? *[Multiple answers possible]*

☐ via a control or radio centre (HUB/Gateway)
☐ via smartphone/tablet
☐ via computer/laptop
☐ via speaker/virtual assistant (e.g., Alexa, Sonos One, ...)
☐ I do not know
☐ Other, namely: *[free entry]*

21. How often do you usually deal with the technical control and adjustment of the functions of your smart home devices?

	Less frequently than once a week	Once a week	Several times a week	once a day	Several times a day	hourly	Several times per hour
Smart Home System	☐	☐	☐	☐	☐	☐	☐

22. Please state below how long you normally use the indicated devices per week. *(Filter from question No. 14)*

	0-2 h	3-4 h	5-6 h	7-8 h	9-10 h	More than 10 h	Do not use
TV	☐	☐	☐	☐	☐	☐	
DVD and Blu-ray devices	☐	☐	☐	☐	☐	☐	
Bluetooth multiroom sound system	☐	☐	☐	☐	☐	☐	
Stationary Computer	☐	☐	☐	☐	☐	☐	
Laptop/Notebook/Netbook	☐	☐	☐	☐	☐	☐	
Tablet	☐	☐	☐	☐	☐	☐	
Gaming console (offline use only)	☐	☐	☐	☐	☐	☐	

23. How often do you speak to your virtual assistant on average? *(Filter from question No. 14)*

By virtual assistant we mean, for example, a smart speaker with an integrated voice assistant (e.g., Alexa).

	Less frequently than once a week	Once a week	Several times a week	once a day	Several times a day	hourly	Several times per hour
Virtual Assistant	☐	☐	☐	☐	☐	☐	☐

24. Please indicate how long your robot hoover is normally used *per week*. *(Filter from question No. 14)*

	1h	2h	3h	4h	5h	6h or more	never
Robot hoover	☐	☐	☐	☐	☐	☐	☐

25. Please indicate how long your hoover is normally used *per week*. *(Filter from question No. 14)*

	1h	2h	3h	4h	5h	6h or more	never
Hoover	☐	☐	☐	☐	☐	☐	☐

26. How many hours *per week* do you spend privately doing the following online?

	0-2 h	3-4 h	5-6 h	7-8 h	9-10 h	More than 10 h	Do not use
Communication (e.g., WhatsApp, email, social media messenger)	☐	☐	☐	☐	☐	☐	☐
Information gathering (e.g., news, reading articles)	☐	☐	☐	☐	☐	☐	☐
Shopping (e.g., online shopping, searching for shops or products, price comparison portals)	☐	☐	☐	☐	☐	☐	☐
Creating content (publish social media posts, websites, blogs, vlogs, videos)	☐	☐	☐	☐	☐	☐	☐

Streaming videos and movies	☐	☐	☐	☐	☐	☐	☐
Streaming music	☐	☐	☐	☐	☐	☐	☐
Playing online video games	☐	☐	☐	☐	☐	☐	☐
Online platforms (e.g. eBay Kleinanzeigen, Kleiderkreisel, BlaBlaCar, ...)	☐	☐	☐	☐	☐	☐	☐

27. When consuming which products or services can you best self-actualize?

Please choose at least 3 of the following product groups and put them in order. Move the product groups about which you best self-actualize to the top.

Clothing
Holiday trips
Kino/Theater
Interior
Digital Devices
Social Media
Online Videos/Streaming
Apps

28. How many of the following products have you purchased in the last three months?

Please estimate the number in each case. If you are not sure whether a purchase falls within this period, include it anyway.

	0	1	2	3	4	5	More than 5
Interior (e.g., furniture, decoration, ...)	☐	☐	☐	☐	☐	☐	☐
Books, magazines (excluding electronic editions, e-books, etc.)	☐	☐	☐	☐	☐	☐	☐
Clothing	☐	☐	☐	☐	☐	☐	☐
Household devices (e.g., hair dryer, hoover, kitchen devices, ...)	☐	☐	☐	☐	☐	☐	☐
Holiday trips	☐	☐	☐	☐	☐	☐	☐
Personal accessories (e.g., jewellery, handbags, purses, ...)	☐	☐	☐	☐	☐	☐	☐
Digital devices (e.g., mobile phone, laptop, speakers, ...)	☐	☐	☐	☐	☐	☐	☐
[Control question] Please select number 2 here.	☐	☐	☐	☐	☐	☐	☐

29. How many square metres of living space does your flat have?

☐ under 20
☐ 20 to under 40
☐ 40 to under 60
☐ 60 to under 80
☐ 80 to under 100

☐ 100 to under 120
☐ 120 to under 140
☐ 140 to under 160
☐ 160 to under 180
☐ 180 to under 200
☐ 200 and more
☐ do not know / no indication

30. Which type of energy do you predominantly use to heat your home?

☐ Electricity
☐ Gas
☐ Fuel oil
☐ Solid fuels (e.g., wood, coal, pellets)
☐ Other (e.g., geothermal energy, solar energy)
☐ do not know / no indication

31. Do you use green electricity?

☐ yes ☐ no ☐ do not know

32. What type of heating is predominantly installed in your home?

☐ Floor heating
☐ Radiator
☐ Wall heating
☐ do not know / no indication

33. Do you heat your home the same during the day and at night, i.e., do you have the same temperature setting all the time?

☐ yes, it is equally warm in the flat during the day and at night
☐ no, the temperatures during the day and at night are different

34. Do you heat your home evenly, i.e., do you have the same temperature setting in all rooms?

☐ yes ☐ no

FILTER: If 33 and 34 no, then:

35. To what room temperature do you heat your living space (living room, kitchen, office) during the day in the heating period?

36. To what room temperature do you heat your bedroom during the day in the heating season?

37. To what room temperature do you heat your living space (living room, kitchen, office) at night during the heating period?

38. To what room temperature do you heat your bedroom at night during the heating season?

FILTER: If 33 yes and 34 no, then:

39. To what room temperature do you heat your living space (living room, kitchen, office) during the heating season?

40. To what room temperature do you heat your bedroom during the heating season?

FILTER: If 33 no and 34 yes, then:

41. To what room temperature do you heat your home during the day in the heating season?

42. To what room temperature do you heat your home at night during the heating season?

FILTER: If 33 and 34 yes, then:

43. To what room temperature do you heat your home during the heating season?

Answer options for each question:

- ☐ <17°C
- ☐ 17°C to below 19°C
- ☐ 19°C to below 21°C
- ☐ 21°C to below 23°C
- ☐ 23°C to below 25°C
- ☐ >25°C
- ☐ do not know → *Filter to question with hand controller for the same combination*

Hand control filter of the respective sub-questions at "do not know" OR

If 33 and 34 no + Do not know anywhere at 35-38, then:

44. To what level do you normally set the hand controls in your living space (living room, kitchen, office) during the day in the heating season?

45. To what level do you normally set the hand controls in your bedroom during the day in the heating season?

46. To what level do you normally set the hand controls at night in your living room space (living room, kitchen, office) during the heating period?

47. To what level do you normally set the hand controls at night in your bedroom during the heating season?

If 33 YES and 34 NO + Do not know anywhere at 41/42, then:

48. To what level do you normally set the hand controls in your living space (living room, kitchen, office) during the heating season?

49. To what level do you normally set the hand controls in your bedroom during the heating season?

If 33 NO and 34 YES + Do not know anywhere at 39/40, then:

50. To what level do you normally set the hand controls during the day in the heating season?

51. To which level do you normally set the hand controls at night during the heating period?

If 33 and 34 YES + Do not know at 43, then:

52. To what level do you normally set the hand controls during the heating season?

Answer options for each question:

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

☐ 6
☐ I do not use hand controls

53. Do you adjust your heating temperature to whether you are at home or not?

☐ yes → *continue with question 54* ☐ no → *continue with question 58*

54. On an average weekday, how many hours are you at home during the day (between 6 am and 10 pm)?

☐ Not at all
☐ 1-3h
☐ 4-6h
☐ 7-9h
☐ 10-12h
☐ 13-15h
☐ 15h or more

55. On average, how many hours a day are you at home at the weekend (between 6 am and 10 pm)?

☐ Not at all
☐ 1-3h
☐ 4-6h
☐ 7-9h
☐ 10-12h
☐ 13-15h
☐ 15h or more

56. What is your average heating temperature in your home when you are not at home?

☐ <17°C
☐ 17°C to below 19°C
☐ 19°C to below 21°C
☐ 21°C to below 23°C
☐ 23°C to below 25°C
☐ >25°C
☐ do not know → *Filter to question with hand controller for the same combination*

Filter: "do not know" for question 56

57. To what level do you normally set the hand controls in your home when you are not at home?

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ I do not use hand controls

58. What type of building do you live in?

☐ Detached single-family house

☐ Semi-detached or terraced house
☐ Duplex house
☐ Residential building with 3 or more flats
☐ Other type of building

59. When was the building constructed?

☐ before 1949
☐ 1949 – 1990
☐ 1991 – 2000
☐ 2001 – 2010
☐ 2011 or later
☐ do not know

60. What is your mode of housing?

☐ owner of a house
☐ owner of a flat
☐ tenant/subtenant
☐ rent-free in a company flat
☐ rent-free in another flat or house

61. How high was your energy consumption on space heating in the last accounting period? *open question*

Please enter the energy consumption of the space heating from your last heating bill (in kWh). You can see an example of this in the picture. If you do not know, please enter "xxx".

62. How long was the accounting period?

☐ Monthly, ☐ quarterly, ☐ half-yearly, ☐ annually, ☐ do not know

63. What is the weather-adjusted characteristic value of your heating consumption per m²? *open question*

This value should be evident from your heating bill. You can see an example of this below. Please enter the value in kWh. If you do not know, please enter "xxx".

64. How many people live in your household, including yourself? *open question*

Please indicate only the number of persons in numerical format. Example: "4" instead of "four"

65. How many of them are children and young people (under 18)? *open question*

Please indicate only the number of persons in numerical format. Example: "2" instead of "two"

66. What is your monthly net household income? Please assign yourself to one of the following groups.

☐ 500€ to below 1000€
☐ 1000 to below 1500€
☐ 1500 to below 2000€
☐ 2000 to below 2500€
☐ 2500 to below 3000€

☐ 3000 to below 3500€
☐ 3500 to below 4000€
☐ 4000 to below 4500€
☐ 4500 to below 5000€
☐ 5000 to below 5500€
☐ 5500€ and more
☐ no indication

67. What is your highest level of education?

☐ School finished without graduation
☐ Primary/Secondary school certificate
☐ Intermediate school certificate
☐ Advanced school certificate (Abitur)/subject-related advanced school certificate
☐ University degree
☐ Academic degree
☐ No indication

68. In which year were you born? *(drop-down menu)*

69. Which gender do you assign yourself to?

☐ female
☐ male
☐ other
☐ no Indication

70. How many inhabitants does the place you live in have?

☐ under 5.000
☐ 5.000 to below 10.000
☐ 10.000 to below 20.000
☐ 20.000 to below 100.000
☐ 100.000 to below 500.000
☐ above 500.000
☐ do not know

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List of publications and appearances

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