Assessing the environmental effects of energy sector digitalization

Evidence from small-scale energy flexibilities

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M.Sc.
Hannes Bluhm
geboren in Rostock
ORCiD: 0000-0002-7175-6302

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Begutachtung: Prof. Dr. Frauke Wiese
Prof. Dr. Tobias Viere

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Hannes Bluhm
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Executive summary

This dissertation investigates the environmental implications of energy sector digitalization, focusing on the flexibilization of small-scale energy technologies, namely photovoltaic systems with and without battery storage, electric heat pumps, and battery electric vehicles in the context of the German energy transition. These technologies are central to achieving an energy system based on intermittent renewable energies and climate neutrality by 2045. In addition, the increasing roll-out of digital infrastructure, along with novel use cases and business models built on it, is expected to enable a more flexible integration of small-scale energy technologies. However, the environmental consequences of these digitalized systems – both beneficial and detrimental – are yet to be fully understood.

The author identifies a research gap in the environmental assessment of digitalization in the energy sector (or 'Smart Energy Systems' (SESs)). While digital technologies are often promoted as tools for automation and efficiency gains, their production, operation, and disposal cause resource use and environmental impacts. In turn, changing consumer behavior and energy system-wide effects can overcompensate or amplify environmental impacts. To address these issues, the dissertation investigates three research directions: identifying the potential environmental effects of SESs, understanding the methodological challenges in assessing these effects via Life-Cycle Assessment (LCA), and evaluating net impacts with a focus on system-wide effects.

In exploring these research directions, the thesis focuses on the first two LCA phases: defining the goal and scope, and inventory modeling. Conceptual and empirical findings are presented through five peer-reviewed papers. Methodologically, the dissertation combines LCA with energy system modeling and social science methods, including reflections on LCA researchers' experiential knowledge, a Delphi workshop with LCA professionals, as well as interviews with and a survey of market players. This interdisciplinary approach allows for a holistic exploration and assessment of environmental effects.

A novelty of the dissertation is the development of a dedicated taxonomy of environmental effects specific to SESs and its application. This taxonomy describes effects at and across three levels: the technology level, including the life cycle of digital devices and effects of optimization and substitution; the user level, covering behavioral changes that are either beneficial, leading to rebounds, or which induce novel demands; and the system level, looking at the macro-scale effects on energy provision and infrastructures. The taxonomy is further specified for small-scale technologies, revealing interactions between effects and

technologies and highlighting that optimization effects – previously regarded exclusively as environmentally beneficial – can also lead to adverse outcomes.

Due to their novelty and the complexity of the environmental effects they generate, the LCA of digitalized energy systems poses specific challenges. The thesis structures these challenges, presents an overview of the main approaches to potentially resolving these challenges, and provides generic research recommendations for considering effects when setting system boundaries and influencing subsequent research efforts in LCAs of SESs.

In terms of applying LCA as an approach, the thesis suggests, for the example of Germany, that the environmental impacts from the production and operation of ICT used in SESs are, though modest, by no means negligible. Selected results for the Global Warming Potential (GWP) indicate that the production and operation of a household with flexibilized PVBS, EHP, or BEV can account for up to 45.1 kg CO_{2eq}/a in 2030. Considering a national roll-out of small-scale technology flexibilization, these values sum up to 0.12 Mt (PVBSs), 0.23 Mt (EHPs), and 0.26 Mt CO_{2eq} (BEVs) in the same year. Compared with reference scenarios without flexibilization, external control of small-scale technologies can result in a GWP relief of -1.6 kg (PVBS), -537.1 kg (EHP), and -168.9 kg CO_{2eq}/a (BEV) arising from changes in the household's electricity supply or optimized technology use (i.e., increased lifetime). However, external control can also lead to additional impacts of up to 1,176.6 kg CO_{2eq}/a (PVBS in 2030) if the household's electricity supply or technology use (i.e., decreased lifetime) is negatively affected. At the level of behavioral effects of SESs, results from PVBSs in 2020 show that, e.g., digital feedback systems can both further enhance environmental performance by -162 kg CO_{2eq}/a and worsen it by an additional 223 kg CO_{2eq}/a – there is evidence for both. Changes in power generation as a systemic effect offer potential environmental impacts of up to -656.2 kg CO_{2eq}/a at the household level for a PVBS in 2018, providing the service of Frequency Containment Reserve, and between 0.17 Mt (PVBSs) and -1.41 Mt kg CO_{2eq}/a (BEVs) in 2030, without assignment to a specific market. In contrast, the systemic effect produced by avoiding power grid expansion is relatively slight.

Comparing more predictable effects from the production and operation of ICT with optimization and systemic effects shows that net GWP impacts are likely to result in net reliefs of -640.5 kg CO_{2eq}/a (PVBS in 2018) at the household, and -0.61 Mt (EHPs) and -1.30 Mt CO_{2eq}/a (BEVs) at the national level in 2030. In the exceptional case of PVBS in 2030, modeling results indicate that flexibilization would result in net burdens of 1,199.5 kg CO_{2eq}/a (household) and 0.23 Mt CO_{2eq}/a (national level). Compared to the remaining emissions gap of 10 Mt CO_{2eq} to reach Germany's 2030 energy sector target in 2024, the outlined GWP savings would account for up to 8.5% of that gap. In contrast, more uncertain user-related effects may lead to both net reliefs and burdens if they become effective on a broad scale. In turn, net impacts of mineral resource depletion, freshwater eutrophication, and ozone depletion from flexibilizing small-scale technologies through ICT are likely to be detrimental.

The dissertation demonstrates that while digitalization can support decarbonization and reduce impacts in additional impact categories, it also leads to environmental trade-offs. Notably, coupling LCA with energy system modeling enables consequential LCA by endogenizing optimization and systemic effects. This approach offers a more realistic and dynamic representation of SESs and tends to result in lower absolute system-wide impacts than attributional approaches. Still, it requires greater research efforts than conventional inventory modeling, which uses annual energy market averages to account for sidestepped or substituted impacts. The approaches reveal that net GWP reductions are achievable but come with increasing impacts in the aforementioned impact categories.

Due to the limited potential for reducing greenhouse gases overall, the author concludes that while digitalization is not a sufficient measure, it is a relevant one for achieving the energy sector's climate neutrality target. Moreover, it represents less a measure for reducing greenhouse gas emissions than a strategy to facilitate the management of a complex energy system with high levels of distributed renewable energy and demand-side electrification. Recommendations to increase environmental benefits and limit additional burdens for industry include adopting sustainability standards for digital infrastructure, improving the design of tariffs to reflect the carbon intensity of the current energy mix, and supporting informed consumer choices. For policymakers, the author suggests enhancing the performance standards of smart meters, integrating environmental criteria into funding schemes, and promoting collaborative research to strengthen the empirical basis for assessments.

Overall, this dissertation contributes to the theoretical understanding, methodological advancement, and empirical evidence base for assessing the environmental effects and resulting impacts of digitalization in the energy sector. It highlights the need for holistic, interdisciplinary approaches and provides practical guidance for future research and policy development.

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a	Annum
ACER	European Union Agency for the Cooperation of Energy Regulators
ADPm	Abiotic Depletion Potential (minerals)
AEE	Authorized External Entity
ALCA	Attributional Life-Cycle Assessment
BEV	Battery Electric Vehicle
BMFTR	German Federal Ministry of Research, Technology and Space
CEER	Council of European Energy Regulators
CLCA	Consequential Life-Cycle Assessment
CLS	Controllable Local System
CO_2	Carbon dioxide
DSO	Distribution System Operator
EC	European Commission
EHP	Electric Heat Pump
EPf	Eutrophication Potential (freshwater)
EProM	Energie-Prosumer-Modell
ESM	Energy System Modeling
eTraGo	electric Transmission Grid optimization
EU	European Union
eq	Equivalent
FU	Functional Unit
GW	Gigawatt

GWP	Global Warming Potential
HAN	Home Area Network
ICT	Information and Communication Technology
IT	Information Technology
kV	Kilovolt
kW	Kilowatt
kWp	Kilowatt-peak
LCA	Life-Cycle Assessment
LMN	Local Metrological Network
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
PVBS	Photovoltaic Battery Storage System
RQ	Research Question
SES	Smart Energy System
SM	Smart Meter
SMGW	Smart Meter Gateway
SMGWA	Smart Meter Gateway Administrator
TSO	Transmission System Operator
VPN	Virtual Private Network
VPP	Virtual Power Plant
WAN	Wide Area Network

Chapter 1

Introduction

This chapter provides a thematic introduction to the ambitions behind energy sector digitalization in section 1.1, before identifying the resulting research gaps and questions regarding the environmental perspective of this transformation process in section 1.2. Section 1.3 defines the research focus and the general approach of this doctoral thesis when it comes to addressing the research questions. Sections 1.4 and 1.5 describe the organizational background and the structure of this thesis.

1.1 Pathways to a flexible, decarbonized energy system through digitalization

Digitalization for the Green Transition

Following the Paris Agreement to limit the global temperature increase to well below 2°C and preferably to 1.5°C compared to pre-industrial levels (UNFCCC, 2016), the European Union (EU) set out the goal of achieving climate-neutrality by 2050 (Directive (EU) 2023/2413, 2023), with Germany, as the most populous member state with the largest economy, aiming for 2045 (KSG, 2019). A key strategy for climate mitigation pursued globally (UNFCCC, 2023), by the EU (Directive (EU) 2023/2413, 2023; Regulation (EU) 2021/1119, 2021) and Germany (EEG, 2023) is the transition away from fossil fuels and towards renewable energy. Consequently, the European Commission (EC) set an interim binding goal of a share of renewable energy in gross final energy consumption of 42.5% and preferably 45% to be jointly achieved by its member states by 2030 (Directive (EU) 2023/2413, 2023). For comparison, in 2023, the share was 24.5% in the EU as a whole and 21.5% in Germany (Eurostat, 2022).

A second strategy pursued by global institutions and the EU for climate change mitigation and sustainable development is the *Digital Transformation* (UN, 2024; Regulation (EU) 2021/1119, 2021), i.e., the process of transforming societies and economies through digital technologies (European Commission and Joint Research Centre, 2022). The EU's focus is on greenhouse gas-intensive sectors, including agriculture, buildings and construction, manufacturing industries, mobility, and energy. In these areas, digital technologies should enable key functions: provision of real-time information via monitoring and tracking, improving process efficiency by simulation and forecasting (e.g., with Digital Twins), dematerializing production and consumption by virtualization, managing complex systems (e.g., with Artificial Intelligence), or supporting interaction with the aid of digital Information and Communication Technology (ICT) (European Commission and Joint Research Centre, 2022).

The linkage and reinforcing nature of both the so-called *Green Transition*, which includes the shift to renewable energy, and the Digital Transformation result in what has been termed *Twin Transition* (Fouquet and Hippe, 2022). The interactions are expected to lead to potential synergies. However, EU institutions also recognize that the Twin Transition may cause tensions and unintended effects that need to be addressed, such as increased energy demand from new data centers and digital appliances, or rebound effects from efficiency gains and cost savings (European Commission and Joint Research Centre, 2022; European Commission, 2022a). Furthermore, Mäkitie et al. (2023) note that there remains a notable lack of conceptual clarity regarding the Twin Transition and how digital technologies can support sustainability transitions.

In the energy sector, digital technologies will be applied to energy supply and demand sides, as well as to infrastructure. New digital business models and services based on these (also referred to as *smart energy* (Kranz et al., 2015)) are expected to make energy systems "more connected, intelligent, efficient, reliable and sustainable" (IEA, 2017). Thus, digital technologies have the potential to significantly support the energy transition, particularly in the power sector, which will continue to undergo a profound transformation in the coming years.

Ambitions towards a decarbonized energy system

The EU and Germany set interim renewable targets for the power sector for 2030 at a share of 69% of the generation volumes (European Commission, Directorate General for Economic and Financial Affairs, 2023) and 80% of the gross electricity consumption (EEG, 2023), respectively. Due to declining costs and the availability of global resources, variable (or intermittent) solar and wind energy are driving the expansion of renewable power plant capacity (UNFCCC, 2023; IPCC, 2023). Energy scenarios by EU electricity and gas Transmission System Operators (TSOs) foresee a share of wind and solar in power generation of 85 to 89% by 2050 across the EU (ENTSOG and ENTSO-E, 2025). These numbers compare to a share of 45.3% in gross electricity consumption in 2023 (Eurostat, 2022). German TSOs suggest shares of 90 to 91% by 2045 for the German power sector (German TSOs, 2024), compared to a share of 52.3% in gross electricity consumption in 2023 (Eurostat, 2022).

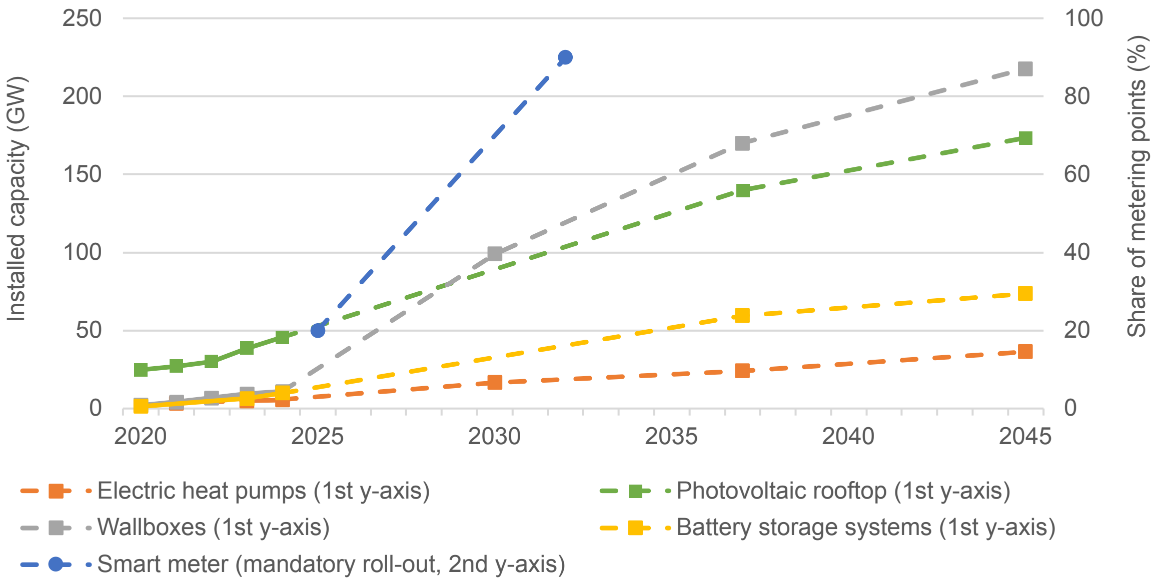

Fig. 1.1 Development of technology expansion in households (actual expansion until 2024, policy targets and projections as of 2025)
Source: author's own depiction based on BNetzA (2025a) with data and assumptions based on KBA (2025), BNetzA (2025b), NOW (2024), BNetzA(2020; 2022), German TSOs (2022; 2024)

To make efficient use of renewable energies, public institutions, independent science, and industry highlight electrification of final energy demand for transport (e.g., by Battery Electric Vehicles (BEVs)), heating (e.g., by Electric Heat Pumps (EHPs)), and industrial purposes as a key strategy (IEA, 2024; IPCC, 2023). Accordingly, household-related, small-scale energy technologies are about to expand significantly beyond current capacities with the goal of achieving a climate-neutral energy system in Germany by 2045 (see Figure 1.1).

By the end of 2024, the installed capacity of the four technologies was 5.5 gigawatts (GW) for EHPs, 9.9 GW for battery storage systems, 10.9 GW for wallboxes, and 45.5 GW for rooftop Photovoltaic (PV) plants. These capacities will increase towards interim political targets for 2030. And based on a middle-ground but ambitious electrification scenario (Scenario

B) of the Network Development Plan 2045 (Version 2025) of the German Federal Network Agency, installed capacities will increase to 36.3 GW for EHPs, 73.7 GW for battery storage systems, 173.4 GW for rooftop PV plants (increasingly together with battery storage systems, hereinafter: Photovoltaic Battery Storage System (PVBS)), and 217.8 GW for wallboxes (cf. BNetzA (2025a) in combination with additional assumptions based on sources documented in Figure 1.1).[1] Also in Europe as a whole, the expansion of small-scale energy technologies by multiples of today's capacities is expected in all scenarios of the Ten-Year Network Development Plan drawn up and agreed upon by the European TSOs (ENTSOG and ENTSO-E, 2025). All three distributed energy technologies increase the connection of households and small enterprises to the electricity system.

Digitalization as an enabler of energy flexibility

Modeling studies by academia (e.g., Zappa et al. (2019); Hansen et al. (2019); Renné (2022)) and industry (e.g., Burchardt et al. (2021)) found that (nearly) 100% renewable power systems with large shares of variable renewable energies and a high degree of electrification are feasible. However, the variability in power feed-in, the increase in overall power demand, and demand peaks due to electrification pose new challenges to the operational management and design of future energy systems (IPCC, 2023). Therefore, they face an increasing need for flexibility, i.e., "[t]he ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions" (Degefa et al., 2021). Flexibility technologies and measures include dispatchable generation, grid-forming converters, expansion of grid interconnections, energy storage systems, and demand-side response (IPCC, 2023).

Due to the profound transformations across the energy system, European bodies expect Europe's flexibility needs to double until 2030 compared to 2021 (European Environment Agency, 2023). On the one hand, scholars have found that the small-scale electrification technologies can themselves provide substantial shares of the rising flexibility needs (Gils, 2014; Kirkerud et al., 2021; Lund et al., 2015). On the other hand, there is a consensus that digital technologies are required to enable flexibility services, thereby facilitating a secure and resilient future energy system while reducing infrastructure investments (IPCC, 2023; IEA, 2017). Technologies include sensors for monitoring, actuators for remote control, and data transmission and processing to safely integrate and coordinate the multitude of additional,

[1] The ranges of the two remaining Scenarios A (lower bound) and C (upper bound) are as follows: EHP: 31.2–38.1 GW, battery storage systems: 59.7–80.9 GW, PV plants: 140.5–190.4 GW, wallboxes: 178.2–218.9 GW.

decentralized energy units into the already complex energy system in near real-time (Weigel and Fischedick, 2019).

Implementation of demand-side digitalization in the EU and Germany

The EU and Germany, as one of its member states, have devised several strategies and passed numerous pieces of legislation focusing on the digitalization of the demand side. Accompanying assessments to EU policies have proposed that digitally enabled demand-side response, including BEVs, EHPs, and PVBSs, could likely provide the demand for flexibility in EU electricity wholesale markets, as well as for ancillary services and congestion management, in 2030 and 2050 (European Commission, Directorate General for Energy et al., 2022) and that small-scale systems are "as essential as large consumers and generators" (European Environment Agency, 2023) for flexibility provision.

One digital infrastructure requirement for active consumer involvement is digital electricity meters combined with communication gateways, collectively referred to as *Smart Meters (*SMs) or *intelligent metering devices*. These devices enable bidirectional communication with external entities and facilitate new services such as real-time power consumption monitoring, innovative electricity tariffs, and feed-in management (Meister et al., 2018).

German regulation provides for the mandatory roll-out of SMs for the following cases (MsbG (2016), § 29(1) & § 45(1) No. 4):

- Consumers with an annual electricity consumption of more than 6,000 and up to 100,000 kilowatt-hours. In the case of households, the lower bound of this range exceeds the average annual electricity consumption of about 2,100 kWh (one-person household) to 5,400 kWh (three-person and more household) of German households (Destatis, 2023). Thus, for households, the range implies the use of larger electric appliances such as EHPs or BEV. According to the German Federal Network Agency, the installation requirement affected 3.5 million metering locations in 2023, including households (BNetzA and BKartA, 2024).

- Controllable consumption units with a capacity of 4.2 kilowatts (kW) and above, including EHPs, battery storage systems, and wallboxes for the charging of BEVs. This requirement affected 1.4 million metering points in 2023 (BNetzA and BKartA, 2024).

- PV plants with a generation capacity above 7 and up to 100 kW, affecting 2.1 million metering points in 2023.

With certain exceptions, 90% of the total stock of these cases will be equipped with SM systems, including control units, by 2032, with an interim goal of 20% until 2025 and additional targets for smaller consumer segments and PV plants. Germany achieved a cumulative roll-out of 15.1% (or 700,624 locations) for the first two cases in March 2025, and responsible entities equipped 1,928 SM systems together with control units (BNetzA, 2025c). For PV plants in a capacity range typical for households of 7 to 25 kW, the SM roll-out was at 1.6% at the end of 2023 (BNetzA and BKartA, 2024). The total roll-out with SMs across standard load-profile consumers (i.e., consumption up to 100,000 kWh) was 2.8% (BNetzA, 2025c), compared to up to 100% in other European countries (ACER and CEER, 2024b). ACER and CEER (2024b) explain these discrepancies in roll-out progress by regulatory differences, with the German regulation being comparatively complex according to Paustian et al. (2025) and Meister et al. (2018).

Furthermore, German regulation provides that energy retail suppliers must offer *dynamic tariffs* (i.e., contracts reflecting price changes at the spot market; see section 2.1.2) as of January 2025 onwards (EnWG (2005), § 41a). Additionally, Distribution System Operators (DSOs) must offer variable grid charges (i.e., time windows with different grid charge levels; see section 2.1.2) as of April 2025 (BNetzA, 2023). In summary, Germany is starting its SM roll-out at a comparably low level. Nonetheless, legislation is providing an infrastructure development path and mandatory services to be offered to households, which are running ahead of the expansion of energy technologies (see Figure 1.1).

In the face of Russia's war against Ukraine starting in 2022, the EC has adopted its action plan "Digitalising the energy system". The plan reiterates the need for an accelerated digitalization of the energy system to reduce dependency on fossil fuels, tackle climate change, and ensure affordable energy access (European Commission, 2022b). For this, the EC urges member states to speed up their SM roll-out (European Commission, 2022b). Furthermore, reports by the European Union Agency for the Cooperation of Energy Regulators (ACER) and the Council of European Energy Regulators (CEER) have recognized the varying extents to which SMs have been rolled out in member states and have repeatedly highlighted the need for a timely roll-out for active consumer integration and facilitation of flexibilization in the form of demand response (ACER and CEER, 2024a; ACER, 2023; CEER, 2022).

1.2 Research gaps and questions

The need to enable flexibility through the use of digital technologies, driven by variable renewable energies and the increasing electrification of the demand side, makes the energy sector a key addressee of the Twin Transition, along with its associated opportunities and risks. Together with challenges related to cybersecurity, data privacy, affordability and accessibility, the above-mentioned assessments and legislations already point out some of the potential environmental drawbacks of digitalization: rising electricity demand created by digital devices and novel infrastructures, increasing material and energy use for their production, as well as changing user behavior that can compensate for potential energy savings achieved (European Commission, 2022a), also known as the *rebound effect* (Gossart, 2015).

Due to the potential multiple effects and the transformative nature of digital technologies, Hilty et al. conclude that: “there is – unfortunately – no guarantee that a smarter solution is a more sustainable solution” (Hilty et al., 2014). The potential for backfiring is why the sustainability implications of digital technology applications need to be assessed: to evaluate their role in achieving carbon neutrality and environmental sustainability, to identify options for mitigating burdens and enhancing benefits, and thus to support informed decision-making (Hilty et al., 2014; Bluhm et al., 2025).

In academia, the environmental assessment of digitalization has become a dynamic field of research, but the holistic understanding of its environmental effects and impacts remains challenging (Charfeddine and Umlai, 2023; IPCC, 2023; Roussilhe et al., 2023). Life-Cycle Assessment (LCA) is a well-established methodology for the environmental analysis of digitalization in general (Bieser and Hilty, 2018a) and smart energy use cases in particular (Durillon and Bossu, 2024). However, although the stock of LCAs on smart energy is growing, the body of holistic LCA literature is still too limited to draw robust conclusions (IPCC, 2023). In addition to the limited availability of quantitatively derived LCAs on smart energy, there also remain several qualitative knowledge and research gaps that I intend to address in this thesis:

1. **Missing guidance on which environmental effects to analyze and how to address methodological challenges**: Several existing frameworks describe and categorize potential environmental effects of digitalization in general (Horner et al., 2016). A fundamental categorization is the division into *direct effects* from the production, operation, and disposal of digital devices, and *indirect effects* which constitute “changes to patterns of production and consumption enabled by ICT in other domains” (Bieser

and Hilty, 2018b), e.g., energy efficiency gains through improved operation of a technical unit. Some studies on digital energy use cases have explicitly consulted such frameworks for their immediate object of investigation (e.g., Wohlschlager et al. (2022); Pohl et al. (2021)). Furthermore, specified LCA guidelines for ICT goods and services provide for the identification of relevant environmental effects (e.g., ITU-T (2023)). However, a holistic taxonomy of environmental effects from digitalization in the energy sector, as well as specifications for small-scale flexibility options from PVBSs, EHPs, and BEVs, are still missing. Thus, one challenge for environmental assessments of smart energy is determining which effects to consider, how they interact, how much effort should be spent on their assessment given their potential relevance, and what their exclusion implies for the overall result (Arushanyan et al., 2014). Furthermore, so far there is no commonly agreed standard methodology for the environmental assessment of smart energy use cases (Durillon and Bossu, 2024). For LCAs of smart energy use cases, several specific methodological questions arise during the assessment, such as how to define the goal and scope elements or how to consider dynamic and future changes (Durillon and Bossu, 2024). In summary, there is a lack of guidance on which effects to analyze and how, leading to inconsistent and difficult-to-compare results in the existing LCA literature on smart energy (Moretti et al., 2017; Durillon and Bossu, 2024).

2. **Lack of quantification of environmental effects, their interactions and net impacts**: Although improving the environmental performance of energy systems and technologies is an oft-stated motivation for research on smart energy, only a fraction of the analyses actually assess their environmental performance. In those cases where they do, the studies often omit the direct effects of digitalization (i.e., the production, operation, and disposal) and neglect to determine net impacts (Durillon and Bossu, 2024). Furthermore, indirect effects of digitalization interact with one another (Hilty and Aebischer, 2015; Ekchajzer et al., 2024). However, only a few LCA studies on smart energy (e.g., Wohlschlager et al. (2024); Xu et al. (2020b)) assess the interaction (or 'feedback loops') of automation processes and so-called systemic effects, i.e., effects of digitalization resulting from the large-scale diffusion of digital technologies (Pohl et al., 2019). However, achieving environmentally beneficial systemic effects, such as improved integration of renewable energy sources, is a fundamental goal for the introduction of digital technologies in the power sector.

3. **Insufficient representation of non-linear relationships**: Depending on the research question, LCA researchers decide whether to assess the product system in scope in

isolation (i.e., Attributional Life-Cycle Assessment (ALCA)) or in interaction with the broader economy (i.e., Consequential Life-Cycle Assessment (CLCA)). The application of both types of inventory modeling can be justified to assess the environmental effects of transformative technologies (Miller and Keoleian, 2015). The CLCA approach can be instrumental in capturing direct and indirect effects and depicting more complex, non-linear interactions (Ekvall, 2020; IPCC, 2023; EC, JRC, IES, 2010; Ekvall, 2020). However, the application of CLCA approaches to assess indirect effects of digitalization is still rare (Pohl et al., 2019). For the forward-looking assessment of the parallel large-scale diffusion of digitalized PVBSs, EHPs, and BEVs in the future energy system and its markets, it appears justified to assume a dynamic relationship among these systems and their surroundings. In contrast, research on the indirect environmental impacts of digitalization typically concentrates on individual applications. It does not capture effects from large-scale diffusion and interactions between use cases, preventing researchers from fully capturing systemic effects (Bieser and Hilty, 2018b; IPCC, 2023). Furthermore, CLCA approaches for BEVs are available (e.g., Wohlschlager et al. (2024); Xu et al. (2020b)), but not for EHPs and PVBSs, nor for interactions among these three. The accurate assessment of such indirect effects of digitalization in LCAs calls for interdisciplinary and integrated modeling approaches (Hilty et al., 2014; Miller and Keoleian, 2015), which are not yet well established (Pohl et al., 2019; Hilty et al., 2014; Durillon and Bossu, 2024).

4. **Environmental assessment beyond greenhouse gas emissions**: Both the direct effects of digitalization and the transition towards renewable energies are known to cause environmentally relevant impacts beyond global warming, such as abiotic resource depletion (Malmodin et al., 2018; Liu et al., 2024). Thus, other things being equal, the trend towards digitalization and the increasing share of renewable energies will drive these impacts. However, environmental assessments of so-called Smart Energy Systems (SESs) including LCAs tend to analyze the greenhouse gas emissions and the global warming potential and omit other impact categories (Durillon and Bossu, 2024; Pohl et al., 2019; Arushanyan et al., 2014). As a result, this narrowed focus can lead to an unreflected shift of burdens from intended reductions in greenhouse gas emissions to greater impacts in other environmental categories, such as resource depletion, which is especially relevant for ICT components (Malmodin et al., 2018). This backfire risk calls for considering a broader, more relevant set of impact categories.

Addressing these research gaps is fundamental to understanding the significance of the intended and unintended effects of energy system digitalization, as well as the resulting net environmental impacts, and to comprehending the consequences of decisions regarding roll-out processes. I intend to further close the outlined research gaps with this thesis and contribute to the overarching goal of understanding the environmental effects of digitalization and its impacts on the energy sector from theoretical, methodological, and empirical perspectives. To achieve this goal, this thesis addresses three overarching Research Questions (RQs):

- RQ1: What are the potential environmental effects of Smart Energy Systems?
- RQ2: What methodological challenges occur when assessing the environmental effects of Smart Energy Systems in Life-Cycle Assessments, and how can they be addressed?
- RQ3: How relevant are the systemic effects of Smart Energy Systems compared to the other environmental effects, and what are the net impacts?

While RQ1 and RQ2 address conceptual and methodological aspects of the environmental assessment of SESs, RQ3 refers to the quantitative extent and proportionality of the environmental effects.

1.3 Research focus and general approach

I address the RQs by assessing one salient field of energy system digitalization, namely the flexibilization of small-scale, household-related energy technologies. More precisely, these technologies include EHPs, rooftop PV plants without battery systems, PVBSs, and BEVs in combination with wallboxes that can be flexibilized via digital infrastructures. These technologies are expected to drive increases in electricity and peak demand during the energy transition, while they are considered to have significant potential to provide demand-side flexibility. I set the regional focus of this thesis on Germany, the most populous and largest economy in Europe. The German power sector is already undergoing a profound transformation, moving towards high shares of variable renewable energies on the supply side and electrification of final energy demand on the demand side, all backed by the goal of climate neutrality by 2045 and by specific interim targets. Accordingly, the German government has passed legislation to facilitate demand-side flexibilization throughout this process. However, measured against the level of the SM roll-out of around 2% in households in 2025 (see above), the degree of flexibilization is still low. Temporally, the focus of this thesis is both backward-looking at past years and forward-looking at future years regarding the facilitation of small-scale energy flexibilities. Regarding environmental effects, I focus on the systemic effects of SESs, their interactions with other effects, and the aggregation of these effects into system-relevant effects.

To quantify the environmental impacts of digitally enabled energy flexibilities from EHPs, PV/PVBSs, and BEVs, I use LCA as a methodological approach. I focus on the first two phases of goal and scope definition and life-cycle inventory analysis, suggesting and implementing different options and strategies. To assess the challenges associated with LCA and to identify environmentally relevant effects and their potential impact, I complement the LCA approach from the field of environmental sciences with Energy System Modeling (ESM) (drawing on an interdisciplinary field of economics, engineering, informatics, and data science), and social science approaches, namely a reflexive approach drawing on experiential knowledge from recent LCA research projects and the Delphi method for LCA professionals' involvement, as well as qualitative, semi-structured interviews and a semi-quantitative survey for market player involvement. Results from social science methods accompany the LCA approach, guiding the focus-setting and reflection on quantitative outcomes. Still, they also stand on their own, representing stakeholders' perspectives on the relevance of environmental effects.

This thesis contributes to the knowledge of digitalization in the energy sector in multiple ways. On the theoretical level, it provides a taxonomy of environmental effects of SESs in general and for flexibility use cases with EHPs, BEVs, and PV/PVBSs in particular, thereby enhancing our understanding of potentially occurring environmentally relevant effects and their interdependence. On the methodological level, the thesis provides guidance for future LCAs on SESs, presenting specific challenges and options for overcoming them. The application and discussion of various types of goal and scope definition and inventory modeling options further enhance the understanding of suitable ways to deploy LCA for SESs. Furthermore, the thesis demonstrates and combines the application of different disciplinary approaches and assesses their suitability for the chosen research focus. Empirically, the thesis enriches the literature on the quantitative environmental impacts of, and beyond, greenhouse gas emissions resulting from the flexibilization of EHPs, BEVs, and PV/PVBSs. Furthermore, it reflects the viewpoints of LCA professionals and German market players regarding the relevance of potential environmental effects of SESs.

1.4 Organizational background

This thesis was written as part of the junior research group 'SteuerBoard Energie – Control mechanisms in the polycentric energy system of the future'. The group was funded by the German Federal Ministry of Research, Technology and Space (BMFTR) within the

Social-Ecological Research funding scheme. The goal of the project was to examine how the concept of polycentricity strengthens the principle of subsidiarity, supports innovation and learning, and fosters greater trust, acceptance, and justice in the future energy system. While one focus of the group was on financing instruments, a second focus addressed the role of digitalization as an enabler of improved organization and sustainability.

1.5 Structure of this thesis

The following chapter (2) provides conceptual background on digital applications in the energy sector, environmental effects of digitalization, and existing work related to this thesis. Chapter 3 details the selected research approach and methodologies. Chapter 4 gives an overview of the individual research articles comprising the cumulative thesis and summarizes the findings and contributions for each research question. The thesis closes with a reflection on limitations and future research directions in chapter 5 and an overarching conclusion and recommendations in chapter 6. Appendices A.2 to A.6 contain the five peer-reviewed academic papers of this cumulative thesis.

Chapter 2

Background

Section 2.1 provides a brief introduction to digital use cases in the energy sector, outlines two key business models for leveraging small-scale energy flexibilities, and explains the basic communication concept for facilitating flexibility with the aid of ICT. Section 2.1.2 provides a general description and categorization of the environmental effects of digitalization, while section 2.1.3 highlights related academic work that the thesis builds upon.

2.1 Digitalization as an enabler of energy use cases and business models

2.1.1 Digital use cases

Several definitions exist for the concepts of digitization and digitalization, with some using the terms interchangeably, while others differentiate between them. Based on a literature review, Frenzel et al. (2021) describe the use of the term *digitization* as "explaining a technical process of data conversion, generation, storage, or processing". In contrast, *digitalization* is being referred to "as a socio-technical phenomenon, the use of digital technologies, and their influence on societies, businesses, and personal lives" (Frenzel et al., 2021). ICT are a prerequisite for digitalization, describing systems used for the "generation, processing, storage, communication, and/or presentation of digital information" (Masanet and Matthews, 2010). Furthermore, the term *smart* is used to describe the characteristics of a system that is digital, connected via ICT, and/or able to process information (Weigel and Fischedick, 2019). Based on Kranz et al. (2015), I refer to *smart energy* as the application of ICT in the processes of energy supply, storage, transmission and distribution, as well as consumption, for various purposes. Weigel and Fischedick (2019) summarize the intended benefits that different stakeholders associate with digital applications in the energy sector as follows: improvement of system stability, environmental protection, energy demand reduction, revenue increase, cost reductions, and satisfaction of customer expectations.

More specifically, digital technologies have enabled numerous use cases in the energy sector. A use case describes a specific goal that a technical system aims to achieve through specified actions, providing value to one or more stakeholders (CEN et al., 2014; Trefke et al., 2013; Cockburn, 2001). Weigel and Fischedick (2019) review digital energy use cases, grouping these into three categories and seven sub-categories (including overlaps):

- **System balancing**: Digital technologies, including sensors, control units, and network connections, enable the management of the increasing complexity resulting from the energy transition process and the balancing of generation, demand, and grid infrastructure. The category includes use cases for (1) remoting monitoring of a system's condition and control of grid assets for load, voltage and frequency control (also referred to as *smart grid*) and optimized operation of power plants, (2) the activation of small-scale and industrial customers via price signals (e.g., variable electricity tariffs) or the aggregation to marketable unit sizes by an external service provider (e.g., a Virtual Power Plant (VPP) operator) for flexibility provision, and (3) identification and prediction of anomalies by the use of advanced data analytics (e.g., forecasts for generation, load and grid conditions).
- **Process optimization**: Digital technologies potentially optimize internal processes. (3)[1] Identification and prediction of anomalies of equipment units, assets, and entire systems can improve their operation and maintenance. Building Digital Twins and using data analytics and machine learning are key concepts. (4) Digital technologies can also support documentation obligations via automation and interconnected Information Technology (IT) systems with stakeholders to improve process efficiency.
- **Customer orientation**: Digital technologies support the fulfillment of increasing customer expectations for affordable and environmentally friendly energy, as well as transparency and convenience. (5) SMs are a key digital infrastructure for smart home applications that facilitate services such as real-time monitoring of energy demand or price-optimized consumption, charging, or feed-in – manually, via remote control, or by automation. Furthermore, neural networks can support the adaptation of energy

[1] Note that Weigel and Fischedick (2019) assign the sub-category *identification and prediction of anomalies* to both the system balancing and process optimization categories. Therefore, number (3) occurs twice.

consumption to customer habits. (6) Digital communication channels, such as online platforms or smartphone messaging applications, can be used for customer interaction. (7) Along the energy value chain and for customer orientation in particular, proof of origin, e.g., renewable energy certificates, can be facilitated via blockchain. These use cases offer the potential to increase trust and transparency.

For the thesis's focus on small-scale energy flexibility, the use-case categories of activating small-scale customers via price signals or aggregating them into larger units (sub-category (2)) and real-time monitoring of energy demand and consumption via digital infrastructure (sub-category (5)) are particularly relevant.

2.1.2 Digital business models

Integrating new technologies into how companies generate and provide benefits and income can change their business models. Change can include the extension, revision, creation, and termination of individual business activities or entire business models (Cavalcante et al., 2011). Driving forces for change include major trends (such as technological or regulatory changes, socio-cultural and socio-economic changes), market forces, macroeconomic forces, and industry forces (Osterwalder and Pigneur, 2010).

Digitalization has accompanied and driven the evolution of business models in various economic sectors, offering new design options (Clauß and Laudien, 2017). In this context, Veit et al. (2014) speak of *digital business models* if digital technologies have a fundamental impact on business operations and the revenues of a company. As of 2015, digitalization has been underpinning the already increasing service orientation of energy companies (Doleski, 2017) alongside other major trends in the energy sector such as decarbonization, decentralization, and democratization (Di Silvestre et al., 2018; Soutar, 2021). Furthermore, Loock (2020) found that digitalization-based business models can address specific bottlenecks in the energy industry that occur due to the interplay of these trends (Loock, 2020), including the change to distributed, intermittent renewable energies and electrification at the household level.

Based on a content analysis of website data of 175 energy firms, Chasin et al. (2020) describe eight emerging archetypes of smart energy business models targeting private households. Two service-oriented business-to-consumer business models are particularly relevant, bearing in mind that this thesis concentrates on flexibility services based on small-scale energy technologies:

- **Smart energy plan provider**: a company offers innovative energy supply plans primarily based on data gathered via smart meters. The offers include data-related services (e.g., non-intrusive load monitoring for detecting inefficient consumer electronics (Aretz et al., 2022)) and innovative tariffs for energy procurement. The latter covers *time-of-use* tariffs, which have varying but predefined prices for fixed time windows (*static time-of-use*) or for varying time windows that require notifications to customers in advance (*dynamic time-of-use*). In the case of *real-time pricing*, prices vary according to changes on the energy wholesale markets. *Critical peak pricing* refers to flat tariffs with occasional higher rates, which customers are informed of in advance. *Critical peak rebates* or *peak time rebates* are flat tariffs designed to incentivize the reducing of electricity consumption by a certain value with prior notification (Nicolson et al., 2018). As of 2025, all German retail energy suppliers are legally obliged to offer real-time pricing to their customers (EnWG, 2005). Based on mandatory self-disclosure, just 90 of about 1,400 German energy suppliers stated that they offered real-time pricing to households (BNetzA and BKartA, 2024). In contrast, a consumer protection organisation found only 20 providers actively offering real-time pricing in the same year (Stiftung Warentest, 2024), while Burger and Rosenow (2025) found 32 German suppliers, based on data collected from April 2024 to March 2025. Reasons for established suppliers not offering such dynamic tariffs might include declining revenue per customer and increasing management costs, e.g., for balancing costs or legally capped billable costs for SM systems, resulting in lower profits (cf. Miletić et al. (2022); Schlund (2025)). In addition to the energy procurement element, *critical peak network tariffs* function similarly to time-of-use, critical peak pricing, or critical peak rebate tariffs. They apply to network charges as another major retail price component (Häseler and Wulf, 2024). In Germany, DSOs are legally obligated to offer three types of variable network charges, including absolute and relative rebates with external activation of load or feed-in reduction, as well as time-varying charges without external control (BNetzA, 2023). These variable tariff options are designed to align customer behavior with market or grid conditions through price signals and incentives, a concept also known as *demand response* (D'Ettorre et al., 2022). Chasin et al. (2020) assign five of 175 researched companies (or of 68 service-oriented companies) to this business model archetype.

- **Distributed energy resources aggregator**: a company offers behavioral incentives to households for activation of energy resources or takes direct control thereof to sell services to the energy exchange or grid operators. The latter covers ancillary services for improved grid quality, including voltage and frequency regulation, congestion relief, so-called 'black start' operations, and power quality, as well as cost-saving services such as resource adequacy or distribution and transmission deferral (Kolenc et al., 2017; Maeyaert et al., 2020). In exchange, the customers earn additional income or save energy. The aggregation of distributed energy resources can potentially replace large-scale power plants (Chasin et al., 2020), a concept reflected in the term *Virtual Power Plant* (VPP). Where some use the terms synonymously, others differentiate between aggregators, as retailers towards households that bundle distributed resources, and operators of VPPs as marketers of services at the wholesale market or aimed at grid operators (e.g., Bertolini and Morosinotto (2023)). Chasin et al. (2020) assign 19 researched companies to this business model archetype.

The remaining six business model archetypes by Chasin et al. (2020) that will not be discussed further here consist of three business-to-consumer models (smart energy management system provider, smart microgeneration & storage provider, smart electric vehicle charging station provider), one consumer-to-consumer model (peer-to-peer energy platform operator), and two business-to-business-to-consumer models (smart utility-in-a-box solution provider, white-label smart device provider). Chasin et al. (2020) further classify these models into service-oriented and product-oriented business concepts.

2.1.3 Digital communication architecture

Enabling the external control services associated with these business models requires a digital communication infrastructure. A simplified, typical configuration based on German regulations is as follows (Setup A in Figure 2.1): a Smart Meter Gateway (SMGW) collects data from one or more modern metering devices in a household via the dedicated Local Metrological Network (LMN)'s security zone. Other devices, such as certified control boxes, that are not certified digital meters, namely Controllable Local Systems (CLSs), are connected via a secure Home Area Network (HAN) channel in the household. The Smart Meter Gateway Administrator (SMGWA) is in charge of authenticating and authorizing passive and active, authorized external entities entrusted by the customer – the former only receiving metering data for services, e.g., invoicing or efficiency monitoring, and the latter being in bidirectional communication with the household for controlling devices (Meister et al., 2018) such as wallboxes, storage systems, PV plants, or heat pumps. For this, the SMGW encrypts and integrity-protects the data before sending it to the Authorized External Entity (AEE) via authenticated channels in the Wide Area Network (WAN). In Germany, the share of smart metering data transmission via the 2G, 3G, and 4G mobile communications standards was 81% in 2023, followed by Powerline Communication (8%) and other data transmission technologies (BNetzA and BKartA, 2024).

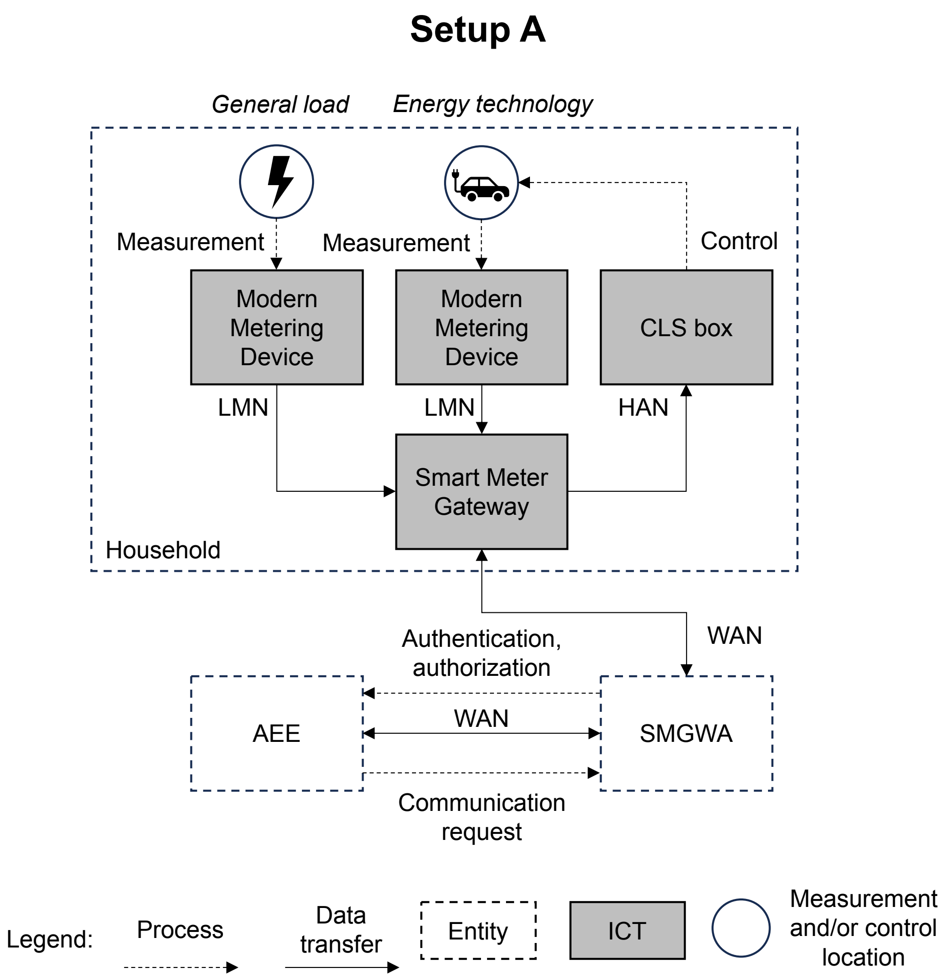

Fig. 2.1 Simplified setup of digital communication for flexibility provision via smart meter infrastructure (Setup A)
Source: author's own depiction

Energy plan providers and aggregators as external entities are establishing communication channels parallel to the SM infrastructure because many of the measurement and transmission intervals are too long for certain system services they intend to provide, and because the use of the SM infrastructure is not legally required for the provision of these services, leading to Setup B in Figure 2.2. The energy plan providers use individual solutions instead, building on built-in or stand-alone ICT devices. To provide ancillary services, they establish a Virtual Private Network (VPN) tunnel via the households' private internet connection or mobile network. The aggregator, in turn, is connected with the control center of the DSO or TSO. The aggregator receives measurement data and information on curtailment capacity and

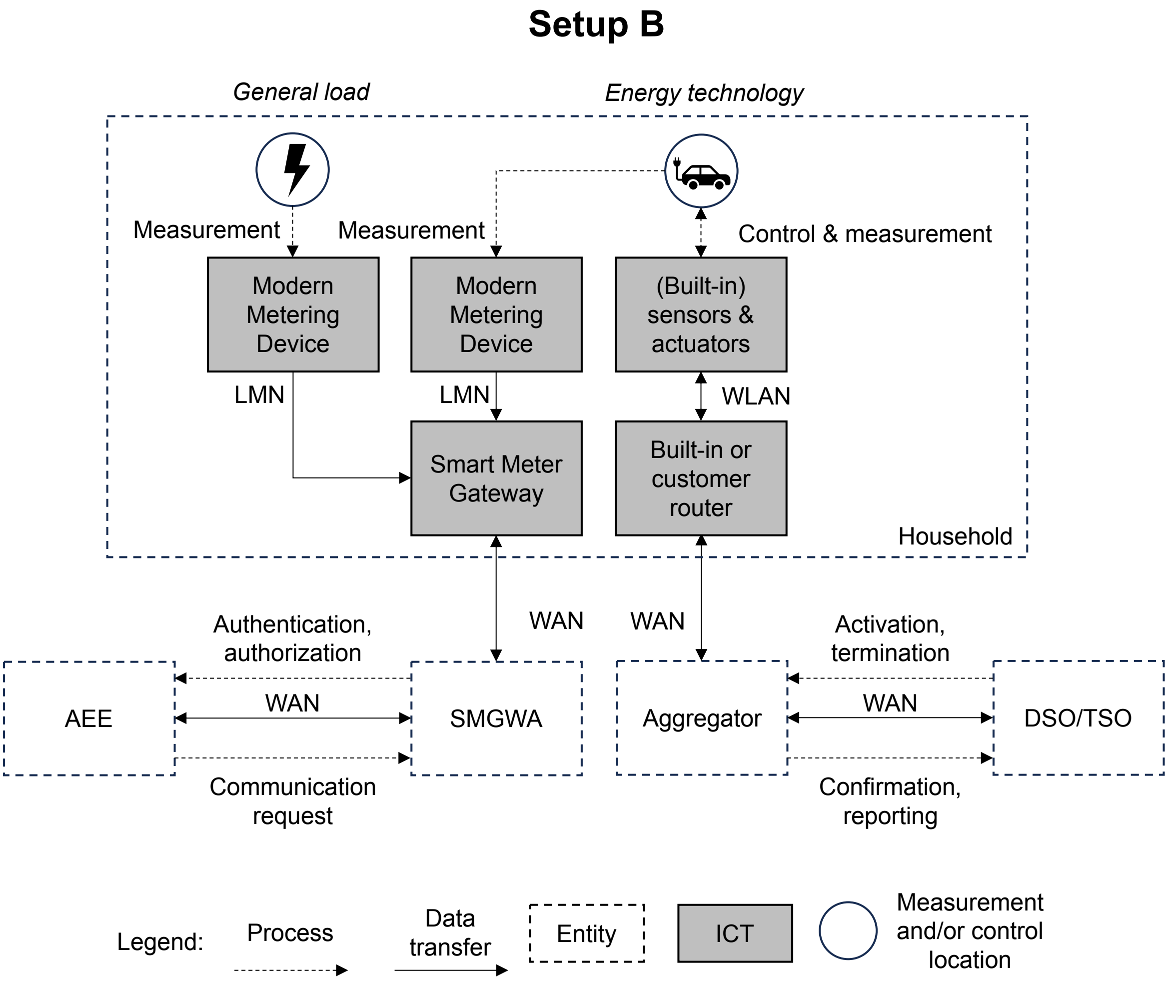

Fig. 2.2 Simplified setup of digital communication for flexibility provision via customer infrastructure (Setup B)
Source: author's own depiction

availability from the household and sends it to the system operator. The DSO/TSO sends an activation signal to the VPP operator, who confirms the activation. The VPP operator then sends dispatch signals to the distributed energy resources. When the desired setting point for load or feed-in is reached, the VPP operator terminates the activation and reports to the DSO/TSO (Kolenc et al., 2017; 50Hertz et al., 2025; Zajc et al., 2019).

Although the use of the SM infrastructure is not legally required for the provision of system services, legally compliant measurement and billing must be carried out via the SM infrastructure. Thus, the ICT equipment of the energy plan provider's individual solution is not sufficient in Setup B and additionally requires modern metering devices, the SMGW, and the associated data transfer to the SMGWA and AEE.

In addition to the communication processes described here, ICT infrastructures are required for customer communication (e.g., customer portals or smartphone applications) and data processing (e.g., servers, computers). For the latter, German TSOs require that the server infrastructure of aggregators must be available with multiple redundancy if they offer system services (50Hertz et al., 2025).

2.2 Environmental effects of digitalization

Scholars have developed several taxonomies to describe the potential environmental effects of digital technologies, which differ in their completeness, clustering, and terminology for indirect effects (Horner et al., 2016). In the following, I present a three-level taxonomy derived from Pohl et al. (2019) and later transpose it to SESs in general and to small-scale energy flexibilities in particular in this thesis. The taxonomy by Pohl et al. (2019) synthesizes several of the aforementioned frameworks and further breaks down behavioral effects.

According to Pohl et al. (2019), environmental effects of digital appliances potentially occur at the technology, use, and system *perspectives* or *levels*. The effects may be intended or unintended by technology providers, operators, and applicants, and they result either in net resource increases (i.e., additional environmental burdens from material and energy demand and other relevant events) or decreases (i.e., additional benefits). The technology level includes direct effects from the production, operation, and disposal of digital technologies, which, by definition, all result in additional resource demand. The technology level covers the standard life cycle of digital devices themselves, as well as data transmission for different services and the service providers' infrastructures. Substitutional and optimization effects are intended phenomena that should enable improved resource efficiency and dematerialization. Substitution effects describe the replacement of products and services by digital technologies. The optimization effect is the improvement of a process enabled by the use of collected and processed digital information (Bonvoisin et al., 2014).

Effects at the user level occur if the digital technology changes user behavior. *Rebound effects* occur when the introduction of the digital product system triggers increased demand for the service it addresses (direct rebound) or other services (indirect rebound) (Gossart, 2015; Galvin, 2015; Coroamă and Friedemann, 2019). Furthermore, digital applications can induce novel demand due to the broader range of available options they offer (Lange et al., 2023), such as the more intensive use of smartphones driven by the variety of applications available, which is an example of an *induction effect*. In contrast to the aforementioned behavioral effects that increase resource demand, *beneficial effects* occur when the application of digital

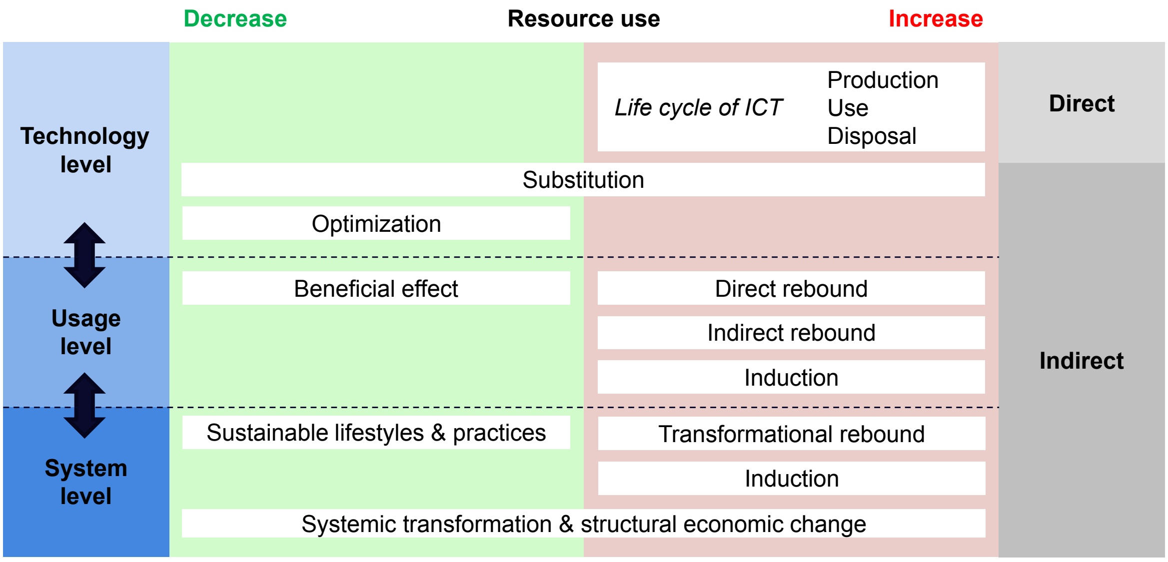

Fig. 2.3 Environmental effects of digitalization
Source: author's own depiction based on Pohl et al. (2019), Hilty and Aebischer (2015), Bieser and Hilty (2018b)

technologies leads to frugal use of them (Santarius et al., 2023) or to more environmentally conscious behavior in other areas of life (also called *positive spillover effects* (Thøgersen, 1999)). Other scholars make further distinctions between rebound and beneficial effects (see, e.g., Santarius and Soland (2018); Lange et al. (2021)). These conceptual considerations are, however, not within the scope of this thesis.

In contrast to the micro-scale effects of individual appliances, system-level effects refer to structural changes at the macro scale that affect entire societies and economic sectors (Horner et al., 2016; Mouthaan et al., 2023). *Systemic effects* occur as a result of the large-scale diffusion and pervasive use of digital applications and the resulting aggregation of rebound, induction, and beneficial effects that can change lifestyles and practices as well as influence economic growth and sectoral changes (Pohl et al., 2019; Mouthaan et al., 2023; Nathan et al., 2007). A general example of systemic effects from pervasive use is the diffusion of internet access into the corporate and private spheres, the subsequent surge in e-commerce, and the associated energy and resource consumption (Horner et al., 2016; Charfeddine and Umlai, 2023).

The environmental effects interact both at and between levels (Bieser and Hilty, 2018b). Whether net impact benefits occur depends on whether direct technology effects can be offset by intended, resource-decreasing effects and the degree to which unintended, resource-increasing effects outweigh benefits. Finally, the effects result in environmental impacts, such as fewer or additional greenhouse gas emissions that drive global warming or absolute differences in the emission of substances that degrade the ozone layer.

2.3 Related work

This thesis touches on several research domains, which I briefly discuss below to the extent that it is relevant to the thesis's context. In so doing, I do not presume to provide a comprehensive literature review but to highlight academic work the thesis builds upon, i.e., conceptual, methodological, and empirical approaches to assess the environmental relevance of digital systems and SESs.

Berkhout and Hertin (2004) introduced a conceptual description and categorization of environmental effects of ICT. Subsequent and complementing work focused on the refinement of the taxonomy (see e.g., Horner et al. (2016); Hilty and Aebischer (2015); Köhler and Erdmann (2004)), more detailed descriptions and typologies of higher-order effects (Hankel, 2014) or specific environmental effects such as rebounds (Coroamă and Pargman, 2020; Galvin, 2015), sufficiency (Santarius et al., 2023), or induction effects (Lange et al., 2023). Further conceptual work has focused on the questions of how to employ digital technologies for sustainable development (Popkova et al., 2022; Sareen and Haarstad, 2021; Hilty and Aebischer, 2015; Kunkel and Tyfield, 2021) or how to design sustainable ICT-based products and services (Preist et al., 2016; Bonvoisin et al., 2014; Li et al., 2015), and partially on sustainable digitalization in certain economic sectors (e.g., Demartini et al. (2019)).

In summary, there is agreement that digitalization triggers a range of environmentally relevant, interacting effects that can be categorized into groups, occurring at the level of individual applications and at the systemic level. Already Berkhout and Hertin (2004) emphasize the pervasive nature of digital applications, the resulting difficulties in measuring and determining the environmental impacts, and the potential for both net positive and negative environmental impacts. Against the uncertain environmental outcomes of cross-cutting digital development, subsequent conceptual considerations focused on conditions, strategies, and policies to limit negative and ensure positive impacts. Notably, these conceptual considerations typically remain at a general level with individual case studies for illustrative purposes. For the energy sector, as a key economic sector affecting sustainable development, a dedicated description bridging the gap between general concepts and anecdotal evidence from individual digital applications is lacking.

A second branch of academic literature comprises empirical research on the usage of ICT-based products and services, e.g., (inter-)national econometric analyses using panel data on digitalization proxies such as the share of population with internet access or ICT-specific indices (Charfeddine and Umlai, 2023), and modeling approaches estimating past and future energy needs for digitalization (Moyer and Hughes, 2012; Bremer et al., 2023; Li et al., 2023; Malmodin et al., 2024; Malmodin and Bergmark, 2015; Bieser et al., 2023; Ullrich et al., 2022), e.g., based on penetration scenarios for data centers, networks, and selected end-use devices. Furthermore, there is a growing body of literature based on field research, e.g., on households using specific digital applications. Regarding energy, several studies have investigated the end users' willingness to use and the actual use and consequences of services based on smart metering, such as increased information on consumption (Zangheri et al., 2019; Batalla-Bejerano et al., 2020), e.g. via disaggregation of consumer profiles for device detection (Carrie Armel et al., 2013; Aretz et al., 2022), or novel tariff systems such as price-dynamic tariffs (Dütschke and Paetz, 2013; Schleich and Klobasa, 2013; Allcott, 2011; Schleich et al., 2017; Klaassen et al., 2016; Nilsson et al., 2017). Another focus has been on smart home systems used to increase energy efficiency or motivate energy-saving behavior (Buckley, 2020; Zangheri et al., 2019).

Although highly context-dependent, the status quo of retrospective and prospective analyses can be summarized as follows: the energy and resource demand of ICT is not negligible, as it already accounted for about 4% of global electricity demand and between 1.4 to 4% of global greenhouse gas emissions around 2020, and it is growing globally, with an emissions increase of 5% from 2015 to 2020, due to the diffusion of existing and novel applications (Bieser et al., 2023; Malmodin et al., 2024). However, country-level studies tend to find a correlation between increasing digitalization and decreasing environmental impacts resulting from indirect effects (Charfeddine and Umlai, 2023). Factual analyses of the energy sector indicate that end-users are open to digital services and products, including automated control. These bear the potential to enable load shifting and absolute reduction in energy demand. Realizing this potential, however, is not guaranteed. E.g., Aretz et al. (2022) show that customer groups that increase their electricity consumption after implementing user feedback systems are as frequent as those that decrease their consumption. To ensure potential advantages, scholars tend to recommend that services and applications should be designed in a simple way and accompanied by transparent information about how they work. For the scope of this thesis on small-scale technologies, the empirical findings suggest that the resulting energy and resource demands are not negligible, given the envisaged large-scale diffusion of SM systems and associated services (see section 1.1). On the other hand, there is reason to expect potential for flexibilization that can be leveraged, provided that decision-makers take end-customer behavior and needs into account.

The relevance and challenges of assessing emerging and transformative technologies with LCA have been the focus of methodological considerations. Challenges include, for example, questions related to dealing with early-stage technologies (Arvidsson et al., 2018; Cucurachi et al., 2018; Van Der Giesen et al., 2020) and technology scaling (Riondet et al., 2024; Bergerson et al., 2020; Pizzol et al., 2021; Miller and Keoleian, 2015), their interactions with surrounding systems (which is equivalent to CLCA (Earles and Halog, 2011; Weidema et al., 1999; Ekvall and Weidema, 2004; Zamagni et al., 2012)), scenario assessments (Börjeson et al., 2006; Bisinella et al., 2021; Pesonen et al., 2000), preparing appropriate inventory data for background processes (Sacchi et al., 2022; Steubing and De Koning, 2021; Maes et al., 2023), and dealing with uncertainty (Lacirignola et al., 2017; Moni et al., 2020; Schaubroeck et al., 2020). In the field of digitalization and smart energy, methodological challenges have been discussed with regard to how precisely to integrate higher-order effects (Pohl, 2022; Börjesson Rivera et al., 2014; Wohlschlager, 2025; Bieser, 2020; Hilty et al., 2014).

Thus, with the diverse further developments, scholars regard LCA as a suitable approach for assessing the environmental impacts of emerging technologies, such as those associated with digitalization, and their dynamic interactions with markets and society, although methodological challenges remain. For SESs, these challenges have been outlined in section 1.2.

On the application side of LCA, several meta-studies examine the digital technologies in scope, the methodological approaches applied, and the results achieved. The studies include reviews of cross-sectoral (Pohl et al., 2019; Arushanyan et al., 2014; Bieser and Hilty, 2018a; Ficher et al., 2025) and sector-specific (Durillon and Bossu, 2024; Moretti et al., 2017; Huck et al., 2024; Andersen et al., 2022) analyses. Regarding the small-scale energy flexibilities within the scope of this thesis, several studies analyze SMs as basic infrastructure (Wohlschlager et al., 2021; Aleksic and Mujan, 2018; Sias, 2017; Weigel et al., 2021) and the necessary infrastructure for smart BEV charging (Wohlschlager et al., 2022) but less so for flexible EHP and PV/PVBS systems.

On the methodological level, the studies repeatedly demonstrate and stress the lack of harmonization and guidelines (see also section 1.2). At the results level of energy-specific analyses, production, operation, and disposal cause relevant environmental impacts, with a concentration in the operational phase (i.e., mainly the electricity consumption of ICT devices and data transmission) and increasing impacts coming with increasing use-case complexity (e.g., bidirectional BEV charging causing more impacts than directional charging).

Furthermore, direct-impact results are sensitive to product design (e.g., materials used) and lifetime. Taking into account impacts from indirect effects, the study landscape indicates potential for net environmental benefits (mainly net greenhouse gas reductions), provided that energy savings or improved energy provision (e.g., via load shifting) can be achieved.

The ever more widespread diffusion of digital technologies and the need for environmental assessments have also led to a surge in guidelines specific to LCAs and environmental footprint approaches on ICT, such as ETSI ES 203 199 (ETSI, 2025) and the ITU-T L.1400 series (ITU-T, 2022, 2023), IEC 62921 (IEC, 2016), IEEE 1680 (IEEE, 2020), EGDC methodology (EGDC, 2024a,b), as well as critical assessments thereof (Coroamă et al., 2020; Bélorgey et al., 2025).

These guidelines support the environmental analyses on a general level, especially for industry purposes. In doing so, they reflect the status quo of established methodological practices. However, for LCA researchers who are focusing on novel digital applications and issues challenging the status quo of established practices, their guiding character is limited. Therefore, a dedicated generation and exchange of scientific knowledge on the LCA of digitalization, including SESs, appear fruitful and are among this thesis's research goals.

In parallel to peer-reviewed research, the body of so-called gray literature has also grown substantially. This includes studies by companies and industry associations (GeSI, 2015; Implement Consulting Group, 2023; Accenture, 2024), and reviews thereof (Bieser et al., 2024), or assessments and reviews funded by public institutions (Gährs et al., 2021a; Stede et al., 2024; EGDC, 2025), or by political parties (Bordage et al., 2021).

Industry-funded studies based on simplified methodological approaches tend to emphasize the sustainability potential of digitalization. Publicly funded studies also identify levers for energy and resource savings. However, they stress the methodological challenges, the lack of robust data, and the need for further research, including into SESs.

It should not go unmentioned that efforts to assess the environmental effects of emerging technologies and digitalization have also elicited conceptual critique. Scholars claim that these are too complex to model with confidence, leading to contradictory results that provide limited guidance to decision-makers (Gritsenko et al., 2024; Freitag et al., 2021). In contrast, a counterargument is advanced that researchers should embrace the uncertainty and complexity inherent in sustainability-related analyses of digital systems. On a practical level, proponents of this view suggest that researchers should conduct qualitative uncertainty analyses, consult a broader circle of experts and stakeholders, and pursue more inter- and transdisciplinary research approaches (Bluhm et al., 2025; Ekchajzer et al., 2024). Nevertheless, the current state of scientific literature when it comes to assessing the environmental effects of digitalization indicates that challenges and research gaps remain (Roussilhe et al., 2023; Hilty et al., 2014).

This thesis follows the second perspective, i.e., although entailing relevant degrees of uncertainty and complexity, the environmental assessment of SESs appears essential, given the situation of the politically mandated large-scale diffusion, the sustainability claim from the industry side, and the lack of adequate analyses considering the characteristics of small-scale energy flexibilities. To deal with the uncertainty and complexity, inter- and transdisciplinary approaches appear suitable.

Other complementing branches of scientific literature related to the scope of this thesis include integration of LCA and ESM for the sake of enhancing ESM by life-cycle impacts of technologies (Blanco et al., 2020; Naegler et al., 2021; Volkart et al., 2018; Rauner and Budzinski, 2017; Xu et al., 2020a; Ekvall, 2020) or to carry out CLCA (Lund et al., 2010; Mathiesen et al., 2009; Le Luu et al., 2020; Mehedi et al., 2021; Gils et al., 2022), energy system analysis on (small-scale) energy flexibility, and the realm of smart energy use cases and business models (Weigel and Fischedick, 2019; Giehl et al., 2020; Chasin et al., 2020; Loock, 2020; Shomali and Pinkse, 2016).

Chapter 3

Research approach and methodology

This chapter provides a general description of the interdisciplinary research approach (section 3.1). It details the chosen methods, i.e., Life-Cycle Assessment (section 3.2), its combination with energy system modeling (section 3.3), and social science approaches (section 3.4).

Tables 4.3 and 4.4 of chapter 4 provide a specification and reflection of the chosen methods, including the advantages identified and the limitations encountered within the scope of this thesis.

3.1 Interdisciplinary research approach

To address the research questions outlined above, I employ an interdisciplinary research approach, drawing on methods from the natural, economic, and social sciences and collaborating with scholars from these disciplines. Furthermore, I adopt transdisciplinary research elements by involving actors outside science in the knowledge generation process (Renn, 2021). The rationale behind this approach is that questions regarding the sustainability of transformative technological developments, such as digitalization, can be described as wicked problems, i.e., complex, ill-defined problems with uncertain solutions (Pryshlakivsky and Searcy, 2013; Seager et al., 2012; Funtowicz and Ravetz, 1993). Addressing sustainability issues as wicked problems calls for inter- and transdisciplinary approaches to find holistic answers that build on "multiple knowledge realms" (Robinson, 2008). In particular, the challenge of assessing digitalization's indirect effects is "inherently interdisciplinary and call[s] for integrated modelling approaches" (Hilty et al., 2014).

Considering my research questions, I chose LCA as the main methodological approach. The use of additional approaches aims to identify potential environmental effects specific to SESs, determine methodological challenges for LCAs of SESs, suggest suitable approaches to solutions, and model the requisite inventory data for the operation of small-scale energy technologies in households and the German power system. The application of social science methods shall also complement the quantitative LCA results with various stakeholder perspectives.

Below, I provide an overview of the methods applied in the research articles of this thesis. More detailed descriptions of the approaches can be found in the individual publications.

3.2 Life-cycle assessment

LCA is a method used to compile and assess the inputs, outputs, and potential environmental impacts of a product or service across its entire life cycle (DIN EN ISO 14040, 2006). It is characterized as being quantitative and natural science-based, considering the life cycle from resource extraction and production to transport and use, and finally to its end-of-life, covering multiple environmental impacts (Rosenbaum et al., 2018). Several general guidelines provide standards and guidance for carrying out LCAs, most notably DIN EN ISO 14040, DIN EN ISO 14044, and the ILCD guidelines (EC, JRC, IES, 2010).

LCA can help companies identify options to improve the environmental performance of a product system. Furthermore, it informs and guides a broader circle of stakeholders for various purposes, such as strategic planning and setting priorities, selecting appropriate environmental performance indicators, and marketing (Pryshlakivsky and Searcy, 2021).

The application of LCA follows four iteratively linked phases. In the goal and scope definition, the overall target concretizes the object of investigation. It specifies the analytical approach, including the system boundaries, the unit processes considered, and the Functional Unit (FU) to which all inputs, outputs, and impact assessment results are related. In the inventory modeling phase, the applicant collects relevant data regarding inputs and outputs. The impact assessment phase involves translating input and output flows into environmental categories. The interpretation phase consists of discussing the results in relation to the research question, including drawing conclusions and making recommendations (EC, JRC, IES, 2010).

A general strength of LCA is that it prevents unreflected burden-shifting between life-cycle stages and across impact categories, thanks to its holistic approach. Furthermore, it is intended to assess average, ideal-type products and not extreme events. A general limitation is that LCA does not calculate actual impacts but the potential of impacts due to uncertainties, simplifications, and generalizations in the modeling. Furthermore, LCA can determine which product system is preferable over another. Still, the method cannot provide normative information on the absolute sustainability of a product system (Rosenbaum et al., 2018).

Due to its holistic consideration of life-cycle stages and impact categories, LCA appears to be a suitable approach for analyzing SESs' multi-level effects and their diverse environmental impacts. Furthermore, performing and evaluating LCAs on SESs remains an active and dynamic field of research, drawing much attention among stakeholders from policy and industry (see section 2.3). Therefore, this thesis can build on existing preparatory work, advance the scientific field, and generate results that can be interpreted and taken up by stakeholders.

3.3 Integration of energy system modeling and life-cycle assessment

Since SESs are still in the early stages of ramp-up, empirical operational data are scarce. Therefore, energy system models facilitate the analysis of SES operation at different scales (household to large-scale energy systems), times (past to future), and determine the resulting effects at the technology and system levels.

Energy system models are simplified, mathematical representations of parts of the energy process chain (Sinha and Chandel, 2015; Pfenninger et al., 2014). They support decision-makers and stakeholders in investigating a system's short-term operation or its long-term development with respect to capacity expansion (Lopion et al., 2018). Their geographic scope ranges from local systems such as households and districts (Kachirayil et al., 2022) to sub-national, national, or supra-regional energy or power systems (Hofbauer et al., 2022; Plazas-Niño et al., 2022).

There are two fundamental approaches to energy system modeling: top-down models depict the energy system as a sector within the economy as a whole (Herbst et al., 2012). In contrast, bottom-up models take a disaggregated view of the energy sector, with greater technological detail (Lopion et al., 2018), including interconnections between energy sectors (Prina et al., 2020). The approach includes, among other features, optimization models that find optimal solutions under constraints, and simulation models that apply predefined rules to depict interactions between elements of a particular system (Herbst et al., 2012).

In this thesis, LCA is linked with two bottom-up models: the simulation model *Energie-Prosumer-Modell (*EProM), which focuses on prosumer households (Wiesenthal, 2023), and the optimization tool *electric Transmission Grid optimization (*eTraGo), which investigates the impact of flexibility measures across sectors in the German energy system (Büttner et al., 2024; eTraGo Developer Group, 2023b).

In general, energy system models and LCAs can be linked in two ways. In ex-post analyses, ESM results are matched with LCA datasets after the model run. In contrast, in endogenous approaches, LCA datasets become part of the energy system model's logic and influence their outcome (Blanco et al., 2020). Thus, endogenous linkage inherently follows a CLCA approach. Furthermore, it requires normative judgment while selecting and weighting impact categories (EC, JRC, IES, 2010; Tietze et al., 2020; Junne et al., 2021).

In this thesis, I employ ex-post coupling approaches. First, to avoid normative judging and second, to avoid the optimization of environmental aspects that are arbitrarily applied to only parts of the energy system (i.e., environmental effects of digitalization for small-scale flexibilities but not for other energy technologies, use cases, and purposes).

3.4 Social science approaches

Social science methods provide an opportunity to integrate different stakeholder perspectives into the research process. This includes the gathering of existing knowledge from and the generic foreshadowing of environmental impacts by scientific and industry experts.

The first social science approach used is a qualitative reflection on experiential knowledge from recent LCA research projects. Experienced LCA researchers contribute structured personal reports reflecting on the methodological and practical challenges encountered and the solution strategies employed during the LCA application to SESs. This also includes a report on my own research experiences on SES LCAs. In the social sciences, this is considered a reflexive approach, in which the researcher's personal knowledge is regarded as a legitimate source of data generation (Fook, 1999). The reflection of existing knowledge addresses the need to gather existing but scattered knowledge and simplify access to it for future analyses.

The expertise and situated knowledge complement the subsequent, more structured Delphi process. The Delphi method is a structured group communication process in which experts assess a specific object about which there is uncertainty and incomplete knowledge. A key element of a Delphi approach is an anonymized quantitative survey used to predict certain developments, which is repeated until a termination criterion is met. It is expected that quantitative assessments will align across reiteration rounds as information and understanding increase. Qualitative assessments of experts can enrich the quantitative survey or serve as the sole focus of the method. Delphi surveys are used to aggregate ideas, predict uncertain outcomes, gather the opinions of an expert group, or build consensus among participants (Häder and Häder, 2022). In real-time, workshop-based Delphi approaches, digital tools enable results to be analyzed without delay, allowing experts to adjust their earlier assessments immediately. Furthermore, anonymity is sacrificed for direct interaction with experts (Gerhold, 2019). For this thesis, I employ the Delphi approach to conduct a group discussion among LCA professionals on topics pertaining to SESs, identifying methodological challenges and potential pathways to solutions, and weighing the challenges of assessing the environmental effects of SESs in light of their potential environmental outcomes. Just like the aforementioned reflexive approach, the Delphi method is intended to support the gathering of existing expert knowledge and perspectives for future analyses.

Guided interviews are a method for obtaining qualitative data in the form of text from an interaction between an interviewer and an interviewee. The interview follows a structured, preset guideline including narrative prompts, pre-formulated questions, cues, or instructions for specific situations (Helfferich, 2022). I conduct interviews with market players from Germany who are already active in the external control of small-scale energy technologies using ICT. The interviews aim to specify the potential environmental effects of small-scale energy flexibilization, which is a necessary step before a quantitative LCA, and for which industry knowledge appears well-suited due to the interviewees' experience with pilot projects and commercial operations.

A standardized survey is a highly structured method that includes questions with predefined response categories (closed questions), without given options (open questions), and hybrid questions, all in a specified order. To assess attitudes, statements are often evaluated using a Likert scale ranging from agreement to disagreement (Reinecke, 2022). For this thesis, I carry out a standardized survey to capture the responding market players' perspectives on the relevance of the previously specified environmental effects of small-scale energy flexibilization. The approach ensures that environmental outcomes can still be effectively assessed even by those actors with in-depth practical expertise but without specific knowledge of LCA as an evaluation approach.

Chapter 4

Overview and synthesis of the research articles

This chapter presents an overview of the research articles that appear as integral parts of this cumulative thesis (section 4.1) and a synthesis of the major findings and contributions for each research question (section 4.2).

4.1 Overview and context of the articles

This cumulative thesis comprises five peer-reviewed articles (Nos. I to V). Table 4.1 gives an overview of the bibliographic references. Table A.1 in Appendix A.1 details the authors' and co-authors' contributions to the publications.

The links between the articles, along with their technological focus, are depicted in Figure 4.1, which also shows their focus on environmental effects and applied methods. Papers I and II have a broad scope in terms of focus and effects. They accompany LCA approaches in identifying environmental effects and in addressing methodological challenges during LCAs, thus addressing RQ1 and RQ2. For this, they build on qualitative and semi-quantitative approaches that incorporate the perspectives of different stakeholders.

Papers III to V involve the application of LCA from conventional to enhanced life-cycle inventory modeling, including both ALCA and CLCA, as well as coupling with simulation-based and optimization-based ESM tools. Furthermore, they focus on one single or several small-scale energy technologies and a selected group of environmental effects. The methodological variety across the papers addresses RQ2 by demonstrating how the environmental

Table 4.1 Publication overview of this cumulative thesis

No.	Publication
I	Wohlschlager, D., **Bluhm, H.**, Beucker, S., Pohl, J., and Fröhling, M. (2023). Overcoming challenges in life cycle assessment of smart energy systems – A map of solution approaches. *Journal of Cleaner Production*, 423:138584, DOI: 10.1016/j.jclepro.2023.138584 (hereinafter: Wohlschlager et al. (2023), see Appendix A.2)
II	**Bluhm, H.** (2025). Environmental effects of ICT-enabled small-scale energy flexibilities: the perspective of German market players. *IOP Conference Series: Earth and Environmental Science*, 1532:012032, DOI: 10.1088/1755-1315/1532/1/012032 (hereinafter: Bluhm (2025), see Appendix A.3)
III	**Bluhm, H.** and Gährs, S. (2023). Environmental assessment of prosumer digitalization: The case of virtual pooling of PV battery storage systems. *Journal of Energy Storage*, 59:106487, DOI: 10.1016/j.est.2022.106487 (hereinafter: Bluhm and Gährs (2023), see Appendix A.4)
IV	Ouanes, N., Kegel, J., Wiesenthal, J., Lenk, C., **Bluhm, H.**, Weiß, J., and Torliene, L. (2022). Prosuming — energy sufficiency and rebound effects: Climate impact of changing household consumption patterns in Germany. *TATuP - Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis*, 31(2):18–24, DOI: 10.14512/tatup.31.2.18 (hereinafter: Ouanes et al. (2022), see Appendix A.5)
V	**Bluhm, H.**, Büttner, C., Cußmann, I., Amme, J., and Wiese, F.. Assessing the environmental effects of digitally enabled, small-scale energy flexibilities: A consequential, multi-level life cycle approach. *Energy Reports*, 16:109520, DOI: 10.1016/j.egyr.2026.109520 (hereinafter: Bluhm et al. (2026), see Appendix A.6)

effects of digitalization, their interdependencies, and effects from large-scale diffusion can be assessed using LCA. The quantitative results and conclusions of Papers III to V focus on addressing RQ3 by presenting quantitative impact assessment results from the application of LCA. In light of RQ2 and RQ3, Paper V is of particular importance as it suggests and applies an enhanced life-cycle modeling approach with dynamic multi-level interaction between the environmental effects of SESs and between small-scale energy technologies.

Five additional (peer-reviewed and non-peer-reviewed) publications on related topics accompany this thesis (see Table 4.2): a comment on the issue of why LCAs in the context of digitalization are relevant for informed decision-making (No. VI), a meta-study on environmental effects of digitalization (No. VII), two technical reports on digital energy use cases with application of LCA (Nos. VIII, IX), and a working paper presenting the current status of research into digitalization for a decentralized energy transition, technical processes, business models, and participation processes (No. X).

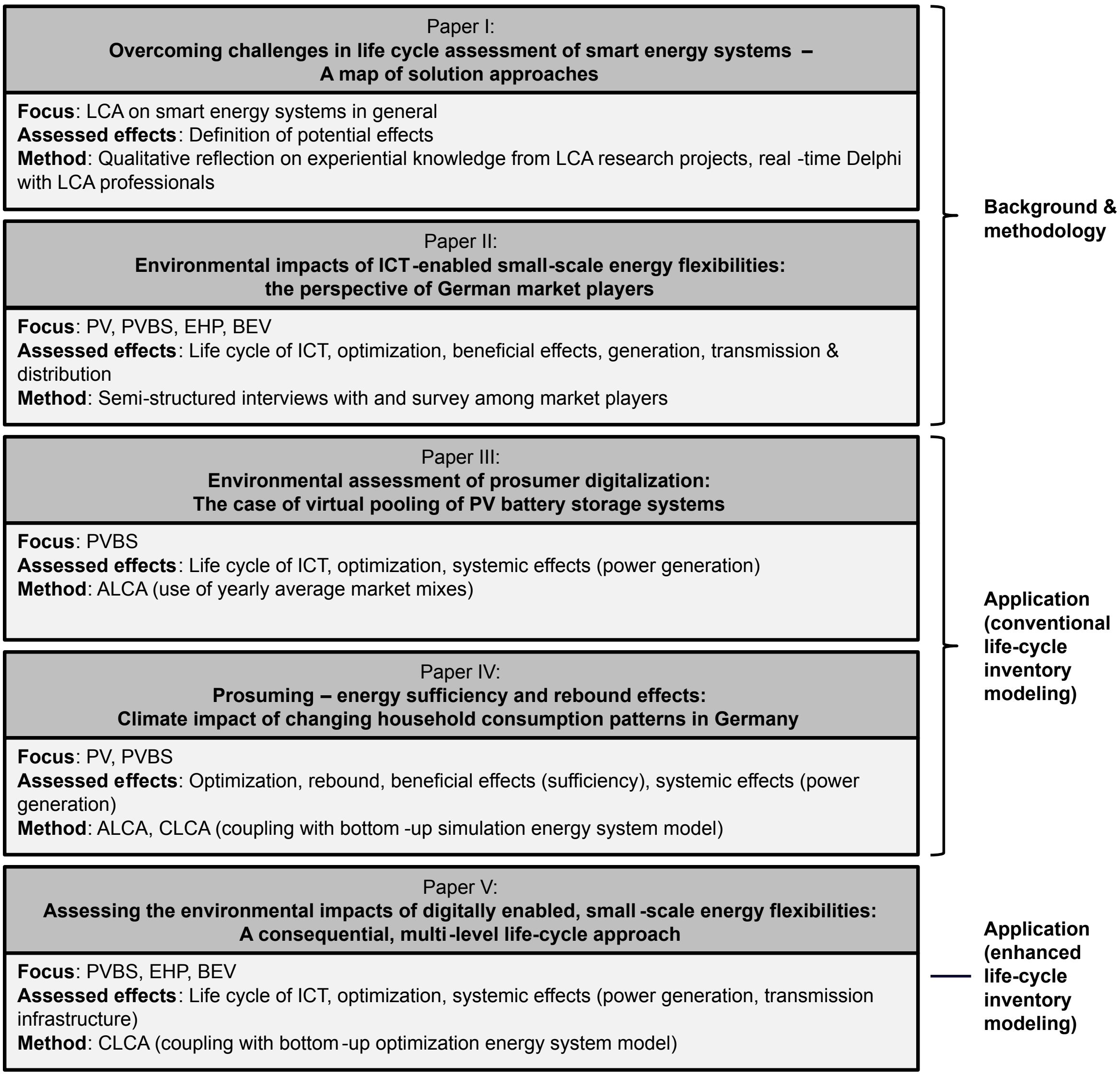

Fig. 4.1 Structure of the individual publications listed in Table 4.1
Source: author's own depiction

Table 4.2 Additional publications

No.	Publication
VI	**Bluhm, H.**, Wohlschlager, D., Pohl, J., Beucker, S., Bieser, J., Schien, D., Widdicks, K., Friday, A., and Blair, G. S. (2025). Understanding digitalization's environmental impact: why LCA is essential for informed decision-making. *npj Climate Action*, 4(1):41, DOI: doi.org/10.1038/s44168-025-00246-1 (peer-reviewed; hereinafter: Bluhm et al. (2025))
VII	Stede, J., Treperman, J., Iglauer, T., Nemec, B., Geilhardt, G., Garber, H., Araujo Sosa, A., Lautermann, C., Schöpflin, P., Schmelzle, F., **Bluhm, H.**, Wehde, L., and Nosova, M. (2024). Metastudie „Nachhaltigkeitseffekte der Digitalisierung" – Eine Auswertung aktueller Studien zur (quantitativen) Bemessung der Umwelteffekte durch die Digitalisierung. Available at: www.bmftr.bund.de (project report for the German Federal Ministry of Education and Research, not peer-reviewed; hereinafter: Stede et al. (2024))
VIII	Gährs, S., **Bluhm, H.**, Dunkelberg, E., Katner, J., Weiß, J., Hennig, P., Hermann, L., and Knauff, M. (2021a). Potenziale der Digitalisierung für die Minderung von Treibhausgasemissionen im Energiebereich. *Climate Change*, 74/2021, DOI: 10.13140/RG.2.2.29837.82403 (project report for the German Environment Agency, not peer-reviewed; hereinafter: Gährs et al. (2021a))
IX	Gährs, S., Weiß, J., **Bluhm, H.**, Dunkelberg, E., and Katner, J. (2021). Erkenntnisse zu Umweltwirkungen von Smart Metern – Erfahrungen aus dem Einsatz von Smart Metern in Europa. *Climate Change*, 34/2021 Available at: www.bundesamt.de (brief study for the German Environment Agency, not peer-reviewed; hereinafter: Gährs et al. (2021b))
X	Gährs, S., **Bluhm, H.**, and Kütemeyer, L. (2022). Sustainable digitalization of a decentralized energy transition. DOI: 10.5281/zenodo.7024801 (working paper of the BMFTR-funded research project 'SteuerBoard Energie', not peer-reviewed; hereinafter: Gährs et al. (2022))

4.2 Findings and contributions

4.2.1 Environmental effects of smart energy systems and small-scale energy flexibilities

Papers I and II address research question RQ1:

- RQ1: What are the potential environmental effects of Smart Energy Systems?

I address this research question with a focus on the environmental effects of SESs in general and for small-scale energy flexibilities in specific.

Environmental effects of Smart Energy Systems in general (Paper I)

In Paper I, the co-authors and I define eight general environmentally relevant technological, behavioral, and systemic mechanisms of SESs that we refer to as *effects*. Compared with a reference system, the effects are associated with increased or decreased energy and resource use, leading to differences in environmental impacts (e.g., greenhouse gas emissions, resource depletion, or ozone layer depletion). The resulting taxonomy is based on the three-level framework proposed by Pohl et al. (2019), as presented in section 2.2. Applied to the arbitrarily chosen example of smart metering that potentially touches on all eight effects, the taxonomy is as follows:

- **Technology level**: the life cycle of ICT includes the production, operation, and disposal of the meter and gateway devices in the household, as well as data transmission to external entities and their ICT equipment (1). Substitution effects occur when a particular product or service is replaced with its digital counterpart (2), e.g., analogue Ferraris meters with SM devices. Optimization effects apply when smart metering data and infrastructure enable additional services (3), such as dynamic tariffs, to automate the operation of household technologies in response to price signals. Dynamic tariffs profit from the positive correlation between wholesale electricity prices and renewable energy shares (cf. Freier and Von Loessl (2022)).
- **User level**: For smart metering, beneficial effects occur when processed and visualized consumption data provide information on inefficient appliances, such as refrigerators, and motivate the switch-over to more efficient ones (4) (see, e.g., Bastida et al. (2019)). On the other hand, customers might choose a larger, more efficient refrigerator model, which, however, increases energy demand in absolute terms, i.e., an example of the rebound effect (5) (see, e.g., Aretz et al. (2022)). Furthermore, the option to assess

consumption data via portals and applications might induce greater use of digital devices, i.e., the induction effect, further increasing energy and resource consumption (6).

- **System level**: Macro-scale effects at the system level can affect energy generation and supply (7), e.g., if the large-scale roll-out of the SM infrastructure results in overall higher or lower energy consumption and affects the temporal demand pattern through demand shifting. Compared with a scenario without SM roll-out, these changes affect the power plant dispatch and its associated environmental impacts. Finally, changes in demand may further affect transmission and distribution infrastructure by increasing or decreasing expansion requirements (8).

As already laid out in earlier taxonomies (Horner et al., 2016; Bieser and Hilty, 2018b), these effects are interconnected at and across levels. Furthermore, whether intended or unintended, these changes might lead to higher or lower resource and energy demand, and thus changing environmentally relevant impacts.

The general taxonomy for SESs in Paper I supports the scoping phase of environmental assessments by universally defining and demonstrating potential environmental effects of SESs. While the defined effects at the technology and user levels align with existing taxonomies of digitalization, major differences arise at the system level. These are presented in a customized way for the energy sector within the wider economy, at a level at which certain small-scale applications can have a notable aggregate effect. The taxonomy shows that positive environmental outcomes are possible. Still, attention should also be paid to unintended effects at the technology, user, and system levels for a truly holistic environmental assessment.

Environmental effects of small-scale energy flexibilities (Paper II)

While the general taxonomy for SESs in Paper I already supports scoping on a general basis, assessments of specific technologies and energy use cases require further definition of relevant effects. Paper II narrows down the answer to RQ1 to the thesis's scope by specifying the taxonomy for small-scale energy flexibilities, namely PV and PVBSs, EHPs, and BEVs. The article builds on five semi-structured interviews with German market players who are active as energy suppliers, aggregators, equipment manufacturers, and TSOs.

While not reiterating the results in detail at this point, three observations will highlight their significance for RQ1. First, the taxonomy of SESs' environmental effects as described above (but also general taxonomies for effects of digitalization, e.g., Pohl et al. (2019)) describes optimization as having a positive impact in itself. However, the mechanisms that interviewees of Paper II articulated for optimization effects suggest that this one-sided categorization might be insufficient. The following question summarizes the finding: Optimization takes place *from the perspective of whom* (which refers to the viewpoint and system boundary and might lead to contradictory outcomes, e.g., for one single household and a national power system), *based on what target* (since optimization results might not be congruent for different targets, e.g., environmental or economic targets), and is assessed *in which environmental category* (since these might correlate negatively, e.g., global warming potential and mineral resource depletion in the case of increased use of renewable energy technologies). Instead of defining optimization effects as inherently positive (meaning they are not considered to constitute optimization if they do not result in a positive impact), I suggest enhancing the respective taxonomies to account for the potential directions of the optimization effect's sign. In other words, it can also result in unintended and potentially adverse environmental impacts. This reconsideration could sensitize actors to environmental risks who use the term 'optimization' for economic optimization strategies, for example. Using the term 'automation' might avoid confusion between normative intentions and the actual environmental outcome.

Second, the taxonomy of environmental effects of small-scale flexibilities in Paper II provides greater detail and draws on industry insights. In contrast to the general SES taxonomy, the effects identified with the aid of interviews are more refined, distinguishing between the specific locations of impact (such as the grid, demand side, supply side, and demand-supply matching), various time scales (including short-term and long-term effects, as well as the pace of change), and the nature of the intended environmental outcomes (such as changes in energy or resource consumption). It also reveals that potential effects can arise from the interplay between small-scale energy technologies within the same household, e.g., if PV/PVBS systems supply a BEV, which in turn bidirectionally stores and discharges electricity via a connection to the public distribution grid. Furthermore, the level of detail achieved for specific effects can already directly serve the inventory phase in LCAs. The direct interaction with industry players has also led to the deriving of various options to improve the environmental outcome of small-scale energy flexibilities (see also chapter 6).

Third, the higher level of detail does not apply to all effects and levels. The interviewees were unable to provide extensive insights about effects at the user level. Statements on effects at the system level remain speculative. Giving presumptive descriptions may be due to limited empirical and theoretical knowledge or motivational biases. Thus, while the interviews have expanded practical and conceptual considerations of environmental effects, industry insights are not necessarily sufficient to paint a complete picture or an equally nuanced portrait of these effects for subsequent scientific assessment.

Nevertheless, both the general taxonomy of environmental effects of SESs in Paper I and the more detailed description of effects of small-scale energy flexibilities in Paper II can help LCA researchers and practitioners, as well as wider circles of stakeholders, to identify and describe effects, and improve related impacts. Identification of relevant effects is not only an essential step for better understanding the technology system in scope but also to comply with specified LCA guidelines for ICT goods and services (e.g., ITU-T (2022; 2023)). Thus, the contribution of these research endeavors to RQ1 consists of a more holistic comprehension of the environmental effects of SESs, particularly small-scale energy flexibilities, which can guide future assessment efforts in science and practice, as well as supporting further conceptual work on the environmental effects of the Twin Transition process.

4.2.2 Methodological challenges and solutions of life-cycle assessments on smart energy systems

Papers I to V address RQ2:

- RQ2: What methodological challenges occur when assessing the environmental effects of Smart Energy Systems in Life-Cycle Assessments, and how can they be addressed?

I address this research question through dedicated investigations into LCA-related challenges and approaches to potential solutions, accompanying assessments, the application of LCA, and an overall reflection. An overview of the methods applied, including their merits and limitations for the focus of this thesis, is provided in Tables 4.3 and 4.4.

Dedicated research on challenges and solution approaches (Paper I)

Paper I is dedicated to challenges and solution approaches in LCAs of SESs. Methodologically, the article builds on a combination of a qualitative, reflexive approach drawing on experiential knowledge from LCA research projects and a real-time Delphi workshop with 16 LCA professionals from research, consulting, industry, and a municipal utility.

Methodological challenges and solution approaches are addressed in four clusters: (1) setting out the playing field of the LCA, (2) definition of the goal and scope elements, (3) collection of data for the life-cycle inventory phase, and (4) consideration of future developments.

By "setting out the playing field", the co-authors and I refer to an internal research 'pre-phase' or 'orientation phase' that is not documented externally within the four standard phases of LCA. This internal phase involves learning about the research object and its effects, considering potential problems and approaches relating to types of analysis used, identifying relevant literature and specific guidance or standards, and narrowing down the research focus in light of the research context and available resources. Even though we are describing general steps applicable to any research process, this orientation phase appears underexamined in the LCA literature in general and in the LCA literature on digitalization and SESs in particular. This gap is all the more important because LCA practitioners are already making landmark decisions at this stage.

Guidance for LCAs of SES use cases remains limited due to their novelty. For orientation, LCA practitioners can seek input from stakeholders and refer to existing general and specific guidelines, use-case classification schemes, industry standards, frameworks on the environmental effects of digitalization, openly available energy data, or meta-analyses. Paper I provides specific sources for each of these options, along with generic research recommendations (see below).

Challenges during the definition of goal and scope elements include the goal setting itself, the choice of reference system, the setting of system boundaries to relevant effects at the technology, user and system levels, the choice of the FU with the utility provided and its temporal extension, defining the temporal reference concerning direction and resolution, defining the variety of geographic references, choosing an inventory modeling approach for the technical sphere and the product, handling multi-outputs, and the selection of impact categories. The co-authors and I give examples for each methodological challenge.

At this point, I want to highlight the empirical findings for setting the system boundaries. The results build on a semi-quantitative assessment by the Delphi workshop participants. We asked them to assess each environmental effect of SESs along two dimensions, using a scale from 1 (low) to 5 (high), based on a hypothetical or generalized SES use case. The dimensions are:

- the potential impact of the effect on LCA results, and
- the challenge of assessing the effect with LCAs.

We found that effects are assessed similarly per level. Effects at the technology level result in a comparably low impact and are less challenging to determine. In contrast, effects at the user level are equally impactful on the LCA results but more challenging to assess. Effects at the system level are both highly relevant to the LCA result and present a notable challenge when it comes to assessment.

Considering the effects' positioning in one of four quadrants and the limited research resources of LCA professionals, we developed generic research recommendations for considering effects when setting the system boundaries. The idiomatically phrased recommendations range from carrying out simplified approaches for groups of effects to focused analysis and exclusion of effects to comprehensive assessment. This heuristic can serve only as a generic rather than universally applicable support to LCA practitioners. LCA applicants need to set actual system boundaries based on consideration of the research question and objective. In addition, the above-mentioned assessment scheme, along with the two dimensions the Delphi participants were asked to consider, may be helpful for practitioners' pre-assessment during the goal and scope definition and orientation phases.

Challenges to data collection include insufficient data availability or outdated data covering technology-level effects, a lack of data for user-related and systemic effects, and obstacles in data validation. These challenges arise from the emerging character of SESs.

Again, efforts to acquire data should be oriented toward the research question and goal. For instance, using generic data from LCA databases for the production, use, and disposal of an SM system may be justified if the analysis focuses on behavioral or systemic effects. However, primary data on the effects at the user and system levels are particularly challenging to obtain. Therefore, research resources should be devoted rather to analyzing these effects. Data collection may be facilitated through interdisciplinary collaboration by involving methods from the social sciences or ESM, for example, gathering field trial data on SM usage in combination with a socio-economic survey collecting data on households' technical equipment, income, age, etc., or by analyzing the impact of large-scale SM roll-out on the power systems' greenhouse gas emissions through an energy system dispatch model. Conversely, if the LCA focuses on the manufacture, operation, and disposal of SM devices, comparatively more effort should be made to obtain current primary data, e.g., a bill of materials and unit processes for manufacturing, assembly, and disassembly from different SM manufacturers. In doing so, LCA applicants could address data validation issues qualitatively through external critical reflection with experts or quantitatively through uncertainty analysis.

Finally, challenges in considering future developments of SESs include the unknown market diffusion of these technologies, the collection of data for foreground and background processes, dealing with the shifting relevance of life-cycle stages and impact categories over time, and considering dynamics between SESs and the surrounding markets.

Scenario development with interdisciplinary experts can help address future and diffusion-related uncertainties. Future-oriented adjustments to inventory data can be facilitated using tools such as prospective life-cycle inventory databases. To capture broader system effects and dynamics, the co-authors and I recommend applying a CLCA approach with ESM, as it can yield significantly different insights compared to results obtained with simplified ALCA inventory modeling. Above all, CLCA can capture the dynamic cause-and-effect relationship between an SES and the surrounding energy market throughout the year, rather than relying on static, annual-average historical data, as is often the case with ALCA approaches.

An illustrative example is the following: SMs enable household energy savings of 10% or about 400 kWh per year. In an ALCA approach, the researcher may multiply the absolute energy reduction by a static, hypothetical average national emission factor of 300 g CO_{2eq}/kWh, resulting in a greenhouse gas reduction potential of 120 kg CO_{2eq}/kWh per year per household. Furthermore, the researcher may multiply the potential by the number of comparable households in the country of interest (e.g., 10 million), yielding an aggregate emission-reduction potential of 120,000 t CO_{2eq} per year. For decision-makers, this figure may be relevant for supporting political targets or for marketing purposes.

In contrast, a researcher pursuing a CLCA may examine the inner-annual demand profile, the hour-specific power plant dispatch, and the changes in dispatch resulting from reduced loads. This may indicate that types of power plant with emission factors above (e.g., natural gas-fired or coal-fired plants with emission factors of about 400–1,000 g CO_{2eq}/kWh (Wernet et al., 2016)) or below (e.g., PV and wind power plants with factors of less than 10 g CO_{2eq}/kWh (Wernet et al., 2016)) the average may be used less intensively, given availability and market mechanisms, e.g., must-run capacity or renewable energy curtailment due to network bottlenecks in the market zone. Considering the inner-annual demand patterns and the cause-and-effect relationship previously mentioned can lead to predicted emission savings that deviate significantly from 120,000 t CO_{2eq}/year. Thus, stakeholders may arrive at different assessments and decisions than in the ALCA analysis. The resulting conclusion for the focus of this thesis is that the CLCA modeling approach better supports the analysis of one key intended effect and impact of consumption- and flexibility-related SES use cases: reducing fossil-based energy supply and saving greenhouse gas emissions on a large scale.

Some of our findings align with existing LCA literature on digitalization, emerging technologies, and energy systems, including challenges in the goal and scope definition (FU, choice of reference, impact categories, temporal and geographical scope, setting of system boundaries etc.), data collection, and considering future changes in the fore- and background (see e.g., Van Der Giesen et al. (2020)). On the other hand, looking beyond the suggested solution approaches of Paper I, some potential goal and scope options for emerging technologies have not yet been commonly applied to SESs, e.g., techniques from prospective inventory modeling such as upscaling from lab to pilot scale (cf. Bergerson et al. (2020)), or CLCA approaches other than integrating partial equilibrium models, i.e., general equilibrium models, input-output analysis, agent-based modeling, system dynamic modeling (cf. Le Luu et al.

(2020)), or combinations of prospective and consequential approaches. This leaves more room for possible solutions than was presented in Paper I (see also section 5.2).

Application of LCA (Papers III–V)

Papers III to V present different practical LCA applications focusing on digitalized small-scale energy technologies. Methodologically, they differ in the definitions of key goal and scope elements, as well as in the type of inventory modeling approach they pursue.

In all papers, the annual consumption of a generic household or the annual power supply of a generic technology unit within a household is modeled. The FU is straightforward to use because the average yearly household consumption volumes and the sizes of technology units are known and comprehensible to stakeholders with a basic knowledge of the energy sector. However, the FU is also associated with a particular viewpoint: the environmental impacts from a single household's or unit's perspective. Decision-makers might be interested in the broader, systemic picture of environmental effects, including aggregated effects, effects that are difficult to attribute to individual households (e.g., avoided large-scale flexibility and transmission infrastructure expansion), and effects generated by the interplay of use cases. Thus, a second FU type in Paper V takes up this angle: the environmental impacts from the entire German power system.

In a backward-looking ALCA approach using historical yearly data for three system services, Paper III incorporates systemic effects arising from the involvement of PVBS while remaining at the individual household level. Paper IV linearly scales the beneficial and rebound effects of a generic PVBS household to the entire German power system, considering both historical and future years up to 2030, and neglecting the standard life cycle of ICT (production, operation, disposal). In doing so, the co-authors and I scaled only those effects identified at the individual household level. While the approaches in Papers III and IV are standard practice in LCA and can be applied with limited effort, they do not capture the inner-annual dynamics in relation to the surrounding market. They are based on lump-sum, exogenous assumptions about indirect environmental effects (e.g., an additional number of load cycles resulting from external control or a percentage increase or decrease in yearly energy consumption to depict behavioral changes). On the other hand, using annual averages enabled the analysis of services in specific markets in Paper III, namely Frequency Containment Reserve, redispatch, and the prevention of renewables curtailment. Against the backdrop of RQ2, ALCA represents a viable inventory solution for analyzing SESs if the LCA's goal is aligned with the approach's limitations and the research resources.

However, Papers III and IV revealed that LCA applicants can only provide a rough analysis of the effects of SESs, namely, providing short-term flexibility via PVBS and the behavioral effects of PV-prosuming by multiplying the lump-sum potentials of specific effects by annually averaged market data or emission factors.

Building on the research experiences reported in Papers III and IV and the shortcomings of ALCA inventory modeling identified for small-scale energy flexibilities, Paper V proposes a dedicated research design. The approach employs the ESM tool eTraGo together with the eGon2035 dataset (eTraGo Developer Group, 2023a) for consequential inventory modeling, focusing on the German power system in the mid-term future (up to around 2030). Three distinct characteristics of the suggested research design distinguish the endogenous modeling approach from previous LCAs of SES and facilitate a more nuanced analysis of SES-specific environmental effects:

- Optimization effects at the household level due to external control of small-scale energy (changes in power volumes and structure and changes in technology usage), as well as systemic effects (changes in power generation, large-scale technology expansion for flexibility, and grid infrastructure expansion) are determined endogenously on an hourly basis. Endogenous modeling with eTraGo sidesteps the need for linear scaling, as well as dispensing with the assumption of single marginal technologies or fixed marginal technology mixes, thus more accurately reflecting market mechanisms and capturing the flexibility potentials embedded in the macro-scale energy system.

- The scenario design and the eTraGo model structure enable the determination of interactions between environmental effects and among three small-scale energy technologies (PVBSs, EHPs, and BEVs).

- The endogenous results allow for analyses of two FUs: the household/unit level and the macro-scale energy system. The approach thereby reveals potential connections as well as possible conflicts between goals.

Coupling of LCA and ESM is by no means a new approach in the relevant scientific literature. However, Paper V is the first to marry both methods in order to analyze the multilayered environmental effects of ICT-enabled small-scale energy flexibilities and the additional effects arising from the interplay among use cases. In so doing, it gives a more holistic view of the environmental impacts of the widespread adoption of digitalization in the energy sector. This enhanced inventory modeling approach comes at the cost of increased research effort and the acceptance of limitations inherent in the time-series disaggregation of the energy system model.

Another methodological challenge arising from applying the taxonomy of environmental effects of SESs to LCA is how to differentiate, assign, and avoid double-counting of optimization and systemic effects. For example, in Paper V, changes in the power plant dispatch are accounted for twice: at the individual household level, an external control alters the SES unit's power off-take and feed-in structure and thus the dispatch and the unit's environmental impacts. The effect is accounted for as optimization in the first of two FUs. At the system level, the scaled effect of changes is accounted for as changes in generation and supply in the second FU (and not as a scaled optimization effect). Furthermore, the system boundaries of the second FU include changes in grid expansion needs and large-scale flexibility technologies as systemic effects, whereas the first FU does not. Thus, the two FUs focus on different system boundaries, yielding results that are not comparable when linearly scaled up or down. Furthermore, for each FU, quantitative results must be assigned to only one effect in the taxonomy to avoid double-counting when calculating net environmental impacts.

Finally, I conducted the impact assessment of Papers III to V using different sets of impact categories. From the quantitative results, I conclude that a sole focus on the Global Warming Potential (GWP), which was the measure in past analyses, is increasingly insufficient for LCAs of digitalization in the energy sector. The one-sided focus was presumably also the case because the GWP is the only obligatory category in the current standard ETSI ES 203 199 (ETSI, 2025) and the second obligatory category besides energy consumption in the ITU-T L.1400 series (ITU-T, 2022, 2023). The reason for the limited suitability of an isolated GWP impact assessment of SESs is that decarbonization, electrification, digitalization, and the introduction of renewable energies shift environmental impacts away from greenhouse gas emissions towards other categories, such as mineral resource depletion, freshwater eutrophication, and ozone depletion, as results show. An extension to a broader set of categories would also more faithfully reflect the role of flexibility for an envisaged, fully renewable energy system. Beyond a specific share of renewable energy, the role of providing flexibility may shift from reducing greenhouse gas emissions to operating and enabling a fully renewable energy system while limiting environmental impacts beyond the GWP.

Future assessments of digitalization-oriented use cases in the energy sector can build on the approaches carried out. Again, this needs to be done with the analysis's context and available resources in mind.

Accompanying assessments (Papers I–II)

As already laid out above, Paper II describes environmental effects related to small-scale energy flexibilities based on interviews. In so doing, the results support the identification of relevant effects and the addressing of challenges during the aforementioned orientation phase and the goal and scope definition. Furthermore, the survey in Paper II provides a semi-quantitative environmental assessment of small-scale energy flexibilities from the perspective of market players, using a Likert scale. While the results stand on their own, the empirical findings are also relevant for LCAs on SESs, e.g., while narrowing down and setting system boundaries to relevant effects or for reflecting on quantitative impact assessment results.

Furthermore, applying social science methods that include personal experience reports from LCA researchers, a real-time Delphi workshop, interviews, and a survey have proven to be viable approaches that require limited effort in addressing the challenges of LCAs on SESs. This finding further contributes to broader academic discussions on how to generate and incorporate diverse types of knowledge into the research process regarding sustainability issues (cf. Brandt et al. (2013); Renn (2021)) and on LCA in specific contexts (Mathe, 2014; Thabrew et al., 2009; Igos et al., 2019).

Table 4.3 Overview and assessment of methods applied – scope and specification

Paper	I		II		III	IV	V
Column	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Goal	Identification of methodological challenges and solutions for LCA of SES	See I(a); generic determination of relevance and assessability of environmental effects of SESs from LCA expert perspective	Identification of environmental effects of small-scale energy flexibilities from market player perspective	Simplified assessment of environmental effects of small-scale energy flexibilities from market player perspective	Detailed assessment of environmental effects of PVBS for different system services	Detailed assessment of environmental effects of PVBS triggered by changes in user behavior	Detailed assessment of dynamics of environmental effects and the interplay of small-scale energy flexibilities
Technology scope	Investigated technologies of evaluated projects	SESs in general	PV, battery storage systems, EHP, BEV	PV, battery storage systems, EHP, BEV, other household appliances	PVBS	PV, PVBS	PVBS, EHP, BEV
Environmental effects identified or assessed	Life cycle of ICT, optimization, rebound, beneficial effects, generation, transmission & distribution	Life cycle of ICT, optimization, rebound, induction, beneficial effects, generation & supply, transmission & distribution	Life cycle of ICT, optimization, beneficial effects, generation & supply, transmission & distribution	Life cycle of ICT, optimization, generation, transmission & distribution	Life cycle of ICT, optimization, generation	Optimization, rebound, beneficial effects (sufficiency), generation	Life cycle of ICT, optimization, generation & supply, transmission
Methodological approach	Evaluation of research projects	Delphi	Interviews	Survey	LCA	LCA	LCA
Concretization of method	Personal reflection of seven publicly funded research projects based on reported experiences and publications	Real-time Delphi with 16 LCA professionals, including semi-quantitative phase and qualitative phase	Semi-structured interviews with five German market players	Survey with Likert-scale items among 18 German market players	FU: Annual power consumption of a generic household, Years: 2020–2030 Scaling: no scaling, Inventory modeling of indirect effects: ALCA, historic (annual averages for specific system services), Impact categories: 7 categories, CML (2016)) and Weidema et al. (2013)	FU: Annual power consumption of a generic household Year: 2018 Scaling: linear scaling of indirect effect Inventory modeling: ALCA (EProM model), CLCA, historic & future (single marginal technology, annual generation averages) Impact categories: 1 category, IPCC (2007)	FU: (1) Annual power supply of generic PVBS, EHP, BEV unit, (2) German power system Year: ~2030 Scaling: linear (direct effects) and non-linear (indirect effects) Inventory modeling: CLCA, future (inner-annual effects and changes in capacity via ESM (eTraGo)) Impact categories: 11 categories, EF 3.1 (Andreasi Bassi et al., 2023)

Table 4.4 Overview and assessment of methods applied – advantages and limitations

Paper	I		II		III	IV	V
Column	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Advantages / merit for the scope of this thesis	Involving researchers' own in-depth experience from LCA application to SES scope, generated knowledge suited for the conceptualization of a subsequent Delphi application, limited effort	Combination of qualitative and semi-quantitative data acquisition, high differentiation of effects in semi-quantitative phase, involving experiences of other LCA experts enables reflection of focus on systemic effects and LCA approach, limited effort	High level of coverage of potential effects and detail regarding effect description, involving experiences of market players enables the consideration of practical insights	High level of coverage and quantification of effects/impacts, involving experiences of market players enables the consideration of practical insights	Depiction of distinct energy markets, limited effort	Coverage and comparison of user-level effects, limited effort	Endogenous determination of indirect technology and systemic effects via ESM, depiction of non-linear effects and technology interactions, consideration of (inner-annual) market mechanisms, differentiation of individual and system perspective via two FUs
Limitations for the scope of this thesis	Limited generalizability (identified challenges and solutions are limited to the scope of the projects), researchers' own biases guiding the subsequent research process	No differentiation between SES technologies and use cases, no impacts in terms of environmental categories, low n	Participants' biases influencing results, limited theoretical & practical knowledge of participants about effects at the user and system level, low n	No differentiation between SES technologies and use cases, no differentiation between effects at certain levels, no impacts in terms of environmental categories, participants' biases influencing results, limited theoretical and practical knowledge on effects at the user and system level, low n	Lump-sum exogenous estimation of effects based on secondary literature, neglect of inner-annual effects	Lump-sum exogenous estimation of effects based on secondary literature, neglect of inner-annual effects, no coverage and comparison to direct effects, missing differentiation between rebounds caused by renewable energies and ICT	Limited possibility of disaggregation of aggregated results and assumptions in the ESM (e.g., time series for PVBS and BEV or grid expansion cannot be traced back to individual units or voltage levels), two FUs are not comparable, no update of the data model to the current network development plan due to high update effort, high effort for method coupling (e.g., for technology matching, data adjustments)

4.2.3 Relevance of environmental effects and net impacts

Whereas RQ1 and RQ2 address conceptual and methodological issues, RQ3 addresses the quantitative results of the LCA analyses:

- RQ3: How relevant are the systemic effects of Smart Energy Systems compared to the other environmental effects, and what are the net impacts?

Applied to the scope of small-scale energy flexibilities in Papers III to V, LCA results show multiple environmental benefits and burdens caused by SESs. Table 4.5 provides an overview of the systems assessed and their GWP results, as evaluated across the three papers. In addition, Figure 4.2 provides a graphical representation of the results. When comparing results, one must consider varying temporal references, methodological differences, and technical system configurations. In addition to the quantitative results, I added the LCA experts' (Paper I) and market players' (Paper II) perspectives for comparison.

Environmental effects at the technology level (Papers III and V)

At the technology level, digitally enabled flexibility increases ICT requirements in the household, for data transfer, and service providers' infrastructure needs. The GWP of devices located in the households (in equivalents (eq) of carbon dioxide (CO_2)) in the non-flexible case is 13.8 kg CO_{2eq} per annum (a) in Paper III for the year 2018 and 18.1 kg CO_{2eq}/a in Paper V for ~2030. The value increases to 14.5 kg CO_{2eq}/a (Paper III) and up to 36.7 kg CO_{2eq}/a (Paper V) in the flexible cases. Differences between Papers are mainly due to different assumptions regarding the necessary ICT equipment and varying secondary data sources used for the life-cycle inventory. The primary impact results from the manufacture of metering devices and, more specifically, from the production of electronic components such as diodes, transistors, and integrated circuits for these devices. Data transfer and the service providers' ICT have a GWP of 1.25 kg CO_{2eq}/a (Paper III) and 0.7 kg CO_{2eq}/a (Paper V). The scaled impact of ICT production around 2030 is between 0.3 Mt CO_{2eq}/a (without flexibilization) and 0.6 Mt CO_{2eq}/a (with flexibilization) (Paper V). These numbers account for 0.4–0.8% of the total GWP impacts of the German power system. Furthermore, Paper V highlights that direct effects cause relatively high shares of Abiotic Depletion Potential (minerals) (ADPm) and Eutrophication Potential (freshwater) (EPf) impacts. The cumulative impacts amount to 37.2–75.1% (ADPm) and 8.6–17.3% (EPf) of the impacts of Germany's power system around 2030.

Table 4.5 Overview of (semi-)quantitative results

Paper	**I**	**II**	**III**	**IV**	**V**		
SES use case	Smart energy systems in general	Small-scale energy flexibility in general	PVBS in VPP for system services	PVBS with user feedback	PVBS with external control	EHP with external control	BEV with external control (directional)
Reference	/	/	PVBS with self-consumption	PVBS without user feedback	PVBS without external control	EHP without external control	BEV without external control
Configuration • Technology • Household consumption or unit input (Ref.)	 / /	 / /	 9 kWp, 9 kWh, 3 kW 4,000 kWh	 3.5 kWp, 3.5 kWh, 3 kW 3,755 kWh	 10 kWp, 10 kWh, 5 kW 2,500 kWh	 3 kW 6,000 kWh	 11 kW (wallbox) 2,250 kWh
Model year	/	/	2018	2020, 2030	∼2030	∼2030	∼2030
The following results refer to...	Potential impact on LCA results (scale from 1 (low) to 5 (high))	Share of responses 'strongly agree' + 'agree' that the effect is positive or negative	GWP (CO_{2eq}) (SES, reference)	GWP (CO_{2eq}) (SES, reference)	GWP (CO_{2eq}) (SES, reference)	GWP (CO_{2eq}) (SES, reference)	GWP (CO_{2eq}) (SES, reference)
Life cycle ICT • Household • Scaled	2.7[1] / /	20% neg.[1] / /	/ 13.8 kg, 15.7 kg /	/ / /	/ 45.1 kg, 22.2 kg 0.12 Mt, 0.06 Mt	/ 45.1 kg, 22.2 kg 0.23 Mt, 0.11 Mt	/ 45.1 kg, 22.2 kg 0.26 Mt, 0.13 Mt
Optimization • Household • Scaled	2.8[1] / /	83% pos., 0% neg.[1] / /	/ (-1.6 – 58.2 kg[2]) /	/ / /	/ 1,176.6 kg -0.01 Mt (PVBS use)	/ -537.1 kg 0.10 Mt (EHP use)	/ -168.9 kg /
Beneficial	2.7[1]	/	/	-162 kg (2020)	/	/	/
Rebound	3.0[1]	/	/	223 kg (2020)	/	/	/
Generation & supply • Household • Scaled	3.9[1] / /	100% pos., 0% neg.[1] / /	/ -656.2 – -12.9 kg /	/ / -3.9 – 5.2 Mt (2030)	/ / 0.17 Mt	/ / -0.83 Mt	/ / -1.41 Mt
Transmission & distribution	4.3[1]	/	/	/	0.6 t (transmission)	18.8 t (transmission)	17.4 t (transmission)
Net impacts • Household[4] • Scaled[5]	/ / /	94% pos., 0% neg.[1] / /	/ -640.5 – 2.8 kg /	/ (-162 – 223 kg[3]) (-3.9 – 5.2 Mt[3])	/ 1,199.5 kg 0.23 Mt	/ -514.2 kg -0.61 Mt	/ -146.0 kg -1.30 Mt

[1] Not assigned to household or scaled; [2] Part of sensitivity analysis and not included in net figures; [3] Scaled effects without consideration of direct effects; [4] All flex vs. No flex scenario; [5] All flex vs. technology-specific scenario

Optimization effects were assessed at the household/unit level and at the macro-scale level. In Paper III, focusing on PVBSs for energy system services, participating households can benefit from improved battery system lifetime, leading to an impact of -1.6 kg CO_{2eq}/a. However, it is not unlikely that they experience reduced battery system lifetime and a lower degree of self-sufficiency. A lifetime reduction of 3.5% (or 0.7 years) results in an additional GWP of 5.7 kg CO_{2eq}/a. Additional emissions arise from the distribution of the environmental impact of the comparatively GWP-intensive battery system production over fewer years. The degree of self-sufficiency may drop by 2.7 percentage points, which could result in additional impacts of up to 58.2 kg CO_{2eq}/a. Here, the additional impact stems from the household's increased procurement of electricity from the public grid to meet demand. Paper V indicates benefits of 8.9 kg CO_{2eq}/a from less technology usage compared to the reference scenario without flexibilization. For EHP households, additional burdens from technology use arise from flexibilization. Differences from the reference case amount to 160.6 kg CO_{2eq}/a. Optimization in the form of technology usage of PVBSs and EHPs is also relevant for cumulative ADPm, EPf, and Ozone Depletion Potential (ODP) impacts. Again, these impacts result from the environmental impact arising from the technology's production being distributed over fewer years. In the case of EHPs, the use of copper, as well as the production of the refrigerant and its partial release during heat pump assembly, are particularly relevant for the devices' environmental impact profile. Comparing the scenario with flexibilization to the scenario without flexibilization of small-scale technologies in Paper V, differences in the power system's overall impact sum up to an additional 0.2 percentage points (EPf), 0.6 percentage points (ADPm), and 2.8 percentage points (ODP).

Environmental effects at the user level (Paper IV)

Behavioral effects were only assessed in Paper IV. Here, observed field data for changes in power consumption of -10 to +20% in prosumer households translate into beneficial effects with an impact of -162 kg CO_{2eq}/a and rebound effects with an impact of 223 kg CO_{2eq}/a in 2020. Linearly scaled beneficial and rebound effects cover impact values from -3.9 to 5.2 Mt CO_{2eq}/a in 2030, depending on the magnitude of effect and the assumed static generation mix of the CLCA approach. However, these values should be viewed as extreme cases: first, because the assumed exogenous range of -10 to +20% of power consumption represents lower and upper limits. Other studies on smart metering and smart home systems found similar extreme values but mutually offsetting effects across their samples (Aretz et al., 2022; Zangheri et al., 2019). Second, multiplying absolute energy volumes by lump-sum emission factors of fossil, single-marginal technologies (such as gas-fired power plants) tends to overestimate GWP impacts compared to more justifiable technology mixes with a lower share of fossil fuels (Lund et al., 2010).

Environmental effects at the system level (Papers III–V)

Effects from changes in generation and supply were assessed in Papers III to V. Using an ALCA approach and not modeling inner-annual dynamics, household-related results from providing specific system services show ranges that cover benefits of -656.2 to -12.9 kg CO_{2eq}/a for the reference year 2018 in Paper III. Coupling LCA with the energy system model eTraGo in Paper V resulted in scaled values from external control, ranging from -1.4 to 0.2 Mt CO_{2eq}/a in ~2030, for changes in generation and supply. The absolute values represent the changes in emissions under flexibilization scenarios in comparison to a reference scenario without flexibilization of small-scale technologies. In relative terms, these values account for -1.6 to 0.4% of the overall GWP impact of the German power supply. Due to the absence of substantial changes in transmission requirements, the respective GWP (and other environmental) impacts are relatively negligible.

Net environmental impacts (Papers III–V) and contextualization

Net GWP impacts cover both total benefits and burdens. In Paper III, netted effects of the life cycle of ICT and changes in generation and supply range from -640.5 to 2.8 kg CO_{2eq}/a per household with PVBS. If optimization effects (which were only part of a sensitivity analysis) were included in the net results, the values would range from -642.1 to 61.0 kg CO_{2eq}/a. Paper IV does not consider direct effects from the production and operation of ICT. However, assuming the scaled PVBS results of Paper V also apply in Paper IV, net impacts would range from -3.8 to 5.3 Mt CO_{2eq}/a. Paper V determines net impacts per unit to be between -146.0 and 1,199.5 kg CO_{2eq}/a, and for the entire energy system to range from -1.30 to 0.23 Mt CO_{2eq}/a. In contrast to unit-related results, system-related results include effects from the avoided expansion of large-scale flexibility and transmission grid capacities.

Placing the results of Paper V in a broader context reveals the savings relevance: the energy sector emissions target is 175 Mt CO_{2eq} in 2030 (KSG, 2019).[1] In 2024, the energy sector emitted 185 Mt CO_{2eq} (UBA, 2025). Considering the remaining emissions of approximately 10 Mt CO_{2eq} to reach Germany's 2030 energy sector target, reveals that the determined GWP savings via small-scale flexibilities in Paper V potentially account for up to 8.5% of that gap.

[1] The sector target for the energy industry includes the combustion of fuels in the energy sector, the transport of energy carriers via pipeline, and fugitive emissions from fuels (KSG, 2019)

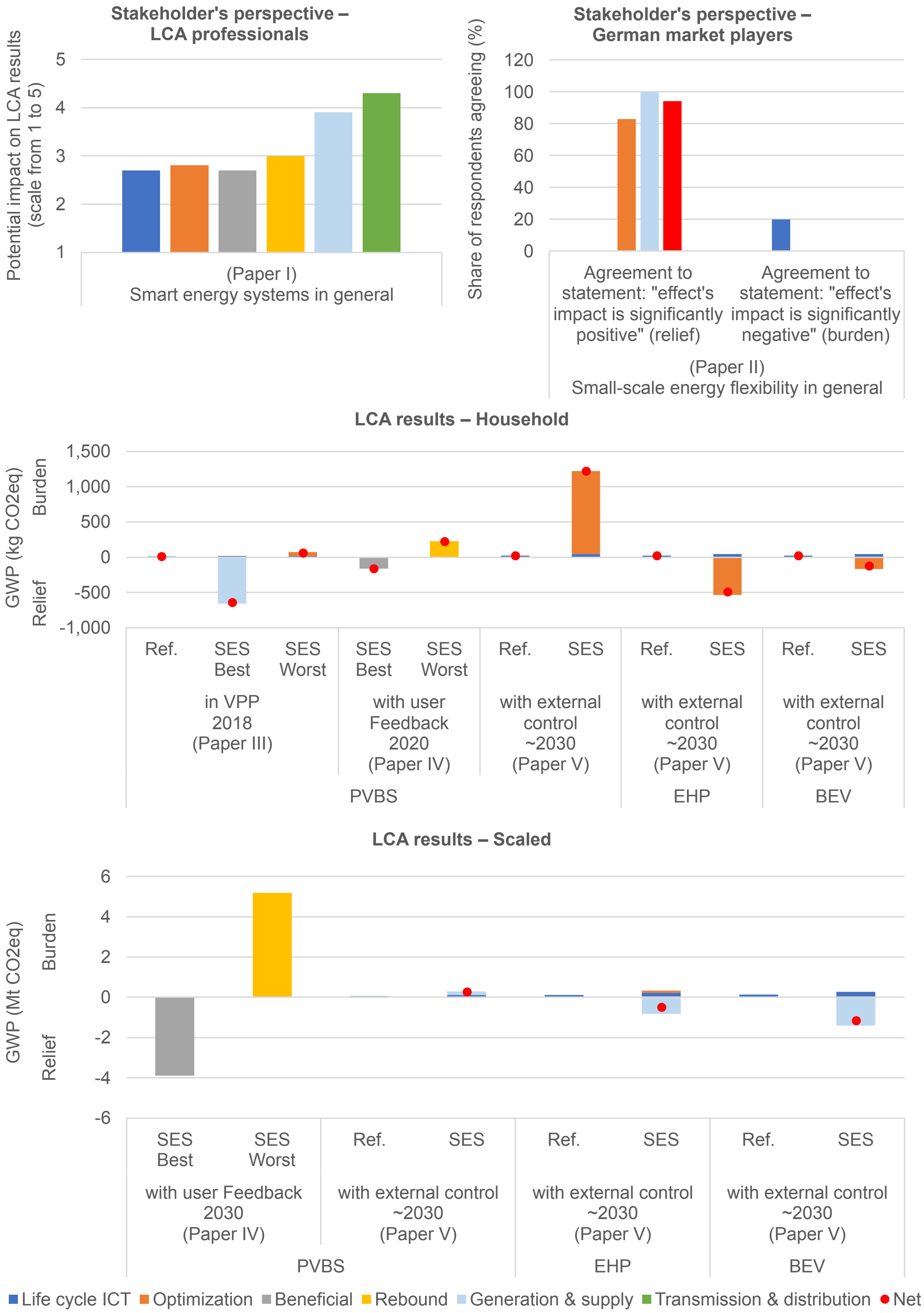

Fig. 4.2 Graphical representation of the (semi-)quantitative results
Source: author's own depiction

Regarding other impact categories, Paper III shows that ICT-enabled flexibilization of a PVBS can result in multiple environmental benefits but also burdens, depending on the system service provided in the year 2018. Preventing renewables curtailment in the grid is entirely beneficial; the provision of a Frequency Containment Reserve is beneficial except for the case of impacts from ADPm; and engaging in redispatch services is beneficial except for acidification, eutrophication, and cumulative energy demand. With a focus on the mid-term future energy system, Paper V reveals that flexibilization outweighs or overcompensates for direct effects in eight of eleven impact categories. However, it is likely to result in higher net ADPm and EPf impacts stemming mainly from the production of additional ICT components, as well as in higher ODP impacts in the event that EHPs are used more intensively.

To make the results of the impact categories beyond GWP tangible, Paper V presents an additional calculation. Whereas the primary analysis considers only the environmental impacts of the exogenous power plant fleet's operational phase (e.g., fossil fuel consumption and associated emissions), the additional analysis also includes the fleet's manufacturing (e.g., mineral resource extraction for plant construction). The figures show that the overall impacts of the German power system in 2030 are significantly higher than in the primary analysis. Thus, the share of impacts of certain life-cycle steps of SESs become significantly smaller: the share of ICT production in the impact of Germany's power system in 2030 changes from up to 75.1% in the primary analysis to 4.4 to 8.9% for the ADPm, and from 17.3% to 1.6 to 3.3 % for the EPf. Thus, the share of impacts from the production of ICT is smaller by multiples but remains relevant. Furthermore, ODP impacts from the production and use of EHPs change from 33.6% to between 6.3 and 6.9%.

Comparison of environmental effects

Although the effects are not directly comparable due to methodological differences, the ranges and orders of magnitudes reveal several overarching insights:

- The standard life cycle of ICT required in the households and by operators causes GWP impacts that can be overcompensated with services based on external control. Overcompensation, however, depends on two aspects: first, the type and magnitude of the impacts achieved at the technology and system levels. As power mixes become more renewable, the potential for GWP compensation is likely to become smaller (other variables being equal). The second aspect involves avoiding or limiting additional burdens caused by other environmental effects at the usage level.

- Behavioral effects are not negligible. They can potentially overcompensate for direct effects from the life cycle of ICT, thereby creating additional benefits. Still, they can also lead to greater impacts in the event of rebounds. What is more, based on empirical data, Aretz et al. (2022) show that both savings and rebounds apply at the same time, depending on the use case and type of household. E.g., the group of prosumer households with digital feedback systems exhibiting beneficial effects saves 20% of electricity on average. However, the group of prosumer households that increased consumption after installing the digital feedback option exhibits a 22% rebound. Across all prosumer households, Aretz et al. (2022) determine energy savings of 0%, and thus neither a tendency toward rebounds nor beneficial effects. Based on literature comparing non-prosumer and prosumer households, we assumed an 18% rebound in Paper IV. The results show that the magnitude of behavioral effects is highly uncertain, but they can cumulate into relevant system-wide environmental benefits and burdens.

- In addition to the conceptual findings in section 4.2.1, the quantitative results show that optimization effects can lead to negative impacts. This applies to the impact categories GWP and ADPm for PVBSs in the case of reduced battery system lifetime and reduced self-sufficiency from the household's perspective, as well as to ADPm, EPf, and ODP for EHPs.

- Effects from avoided expansion of transmission infrastructures (110–380 kilovolts (kV)) are minor and do not generate significant environmental relief.

- Results from the household and overall system perspectives align, as they point in the same direction, given a consistent methodological context as applied in Paper V.

- In terms of the cumulative benefits and burdens, the relevance of the small-scale energy flexibilities differs. Differences occur because the number of units and their specific rated power, capacity, and availability vary, with BEVs exhibiting a high envisaged diffusion (15 million in 2030) and beneficial technical characteristics (storage capacity of up to 100 kWh and beyond per BEV and rated power of 11 kW per wallbox, year-round availability), leading to greater relevance as compared to EHPs, followed by PVBSs.

- Net GWP benefits are achievable. However, these will not come without environmental impacts triggered by certain effects (most notably inevitable direct impacts from the life cycle of ICT involved) and a potential shift of burdens towards other impact categories. Without considering behavioral effects, the overall tendency of technology and system-level effects is as follows: the more flexibility enabled via ICT, the less GWP and Photochemical Ozone Creation Potential (POCP), but the more ADPm, EPf, and ODP.

- The chosen methodological approach significantly impacts the LCA results. The more detailed inventory modeling approach that considers inner-annual effects leads to a narrower range of impacts. On the one hand, this is due to key assumptions regarding emission factors of substituted or avoided energy carriers. On the other, the lump-sum linear scaling technique in Paper III assumes a continuously available and fully utilized potential for ancillary services. In contrast, technology usage is endogenously determined in Paper V. Thus, with the same parametrization, endogenous modeling is likely to lead to lower (and more realistic) usage and, consequently, lower differences in impacts compared to the reference system.

Overall, the environmental impact of small-scale energy flexibilization varies according to the effects considered, use cases, time period, impact categories and method applied. While digitalization does not come without burden shifts, it offers levers for net environmental relief in terms of GWP and other impacts.

Chapter 5

Limitations and research outlook

This chapter assesses the limitations of the thesis in section 5.1 and provides an outlook on potential future research in section 5.2.

5.1 Limitations

General limitations of the applied methods for the scope of this thesis have already been laid out in section 4.2.2 and Table 4.4. Further limitations arise from the interdisciplinary approach, the LCA-specific methodological choices, and the underlying data and assumptions.

Despite the benefits of interdisciplinary research, such approaches come with potential pitfalls. Reflected against the background of this thesis, these include the following incompatibilities:

- **Varying scope**: Despite the delineated focus of this thesis, the results are not unconditionally comparable across publications due to differences in scope. Varying elements include differences in the particular technology in focus (SESs in general, PV/PVBSs alone or in comparison or combination with BEVs and EHPs), environmental effects, or the temporal reference (particular year in the past or future or none). Although the varying scope limits the generalizability of results and conclusions, it allowed for addressing the three research questions that refer to distinct aspects along the LCA research process, assessing a broader spectrum of general and specified use cases, focusing on particular effects, and involving industry and LCA experts who may be unfamiliar with specific conceptual considerations or who have only general or specialized knowledge about individual SES technologies.

- **Knowledge integration**: A barrier to the integration of results is not only the varying scope but also the combination of qualitative and (semi-)quantitative results (here, text from interviews and project reports with survey, Delphi or LCA data), as well as different scales of (semi-)quantitative results (ordinal scales from survey and Delphi and metric scales from LCA).

- **Methodological focus**: Despite the interdisciplinary approach of the thesis, its methodological focus is on LCA. This results in an unbalanced application of the methods. On a practical level, my scientific training as an industrial engineer also limits the depth of the social science methods I applied, given my limited experience and background.

The application of LCA in the context of the thesis also has specific limitations. First, the limited generalizability of results also applies to the Papers with dedicated LCA applications, given the varying goal and scope definitions.

Second, Ficher et al. (2025) showed that the end-of-life phase of ICT products can significantly affect their life-cycle impacts, depending on the end-of-life scenario, methodological choices, and impact category. Therefore, the cradle-to-gate plus use phase focus of this thesis might result in the omission of a relevant share of total life-cycle impacts of SESs. Whether this results in an over- or underestimation depends on the chosen allocation rules. In the quantitative LCA studies of this thesis, the cut-off approach was applied. The approach does not grant environmental credits for recycled materials in the end-of-life phase but does consider the environmental impact of waste processing (Wernet et al., 2016). Thus, the combination of the cut-off approach and omission of the end-of-life phase underestimates the resulting environmental impact.

Furthermore, effects at the distribution grid level have not been considered, although these are relevant for assessing the potential benefits and burdens of SESs. For BEVs, Wohlschlager et al. (2024) showed that different charging strategies result in varying low-voltage grid expansion needs, with price-optimized bidirectional charging triggering an additional 98 kg CO_{2eq} per vehicle and year in 2040, and thus multiples of the ICT infrastructure's impact. In contrast, a BEV fleet charging according to a mix of direct, price-optimized, and vehicle-to-home charging triggers only 3 kg CO_{2eq} per vehicle per year in low-voltage grid expansion. In conclusion, neglecting effects at the distribution grid level underestimates the net environmental impact of small-scale energy flexibilities. The extent, however, depends on the baseline scenario and the specific use-case scenario.

Third, the foreground data on ICT elements from secondary literature and the background data from LCA databases were not adjusted for potential future changes, such as emission reductions during manufacturing or increases in recycling quotas. Prospective LCA approaches based on Integrated Assessment Models with varying socio-economic narratives indicate a likely shift in environmental impacts due to technological changes. For example, Sacchi et al. (2022) demonstrate that the average global impacts from energy provision are expected to cause more metal depletion and ozone depletion in scenarios with a maximum 2°C global temperature increase. In contrast, other impacts are decreasing, or their trajectories vary across Integrated Assessment Models (Sacchi et al., 2022). Impacts from future changes might be limited due to the mid-term perspective (up to 2030) in Papers IV and V. However, they likely overestimate GWP impacts, given the implementation of national and global decarbonization ambitions, and there is also an expected shift towards other environmental categories. For SESs, the product- or service-specific impact is hardly predictable without dedicated analysis.

Fourth, the coupling of LCA and ESM is subject to specific limitations. These include mismatches between the energy technology data used from the LCA database and the eTraGo data model (e.g., scales, efficiencies, temporal, and geographical references). Again, the influence on the quantitative impact result is linked to the chosen non-prospective approach (see above). On the other hand, the technology-matching approach via energy efficiencies in Paper V may be suited to depicting direct emissions from fuel combustion, but less so to material input-output ratios of thermal power plants. If material efficiency gains are actually lower than energy efficiency gains, the chosen matching approach underestimates the resulting environmental impacts, and vice versa. Furthermore, the eTraGo model has been developed for energy system planning and does not depict specific energy markets, regulations, or certain technical characteristics (e.g., partial-load efficiencies of power plants). Finally, the analysis of interconnected environmental effects is simplified because it does not include a detailed model of battery degradation of PVBSs or compressor starts of EHPs, and it assumes continuous linear scalability of large-scale flexibility and grid capacities.

5.2 Research outlook

Based on the above-described limitations and drawing on the exploration of the research questions, I suggest the following potential future research topics:

- For a more complete and profound picture, further research could complement the identification and understanding of environmental effects of SESs via alternative, collaborative methods such as group model building or causal loop diagrams as suggested by Ekchajzer et al. (2024).

- Future research could expand the focus of SESs and small-scale flexibilities in several ways: use cases supported by artificial intelligence as a topic that is now drawing increasing research attention, bidirectional charging of battery electric vehicles together with multi-level effects, broader analyses of interactions between use cases including varying degrees of flexibility to identify potential non-linear benefits and burdens of market diffusion, and analyses beyond 2030.

- To more accurately depict the impact of actual external SES control, energy system modeling could integrate market agents' behavior with their dispatch strategies via agent-based models, the impact of different policy options, and the influence of (dynamic) energy price components, or the models could build on increasingly available empirical data (see next bullet point).

- The ongoing roll-out of digital technologies, use cases, and incentive structures provides increasingly real-world data that can be used for LCA, and combined socio-economic research. This includes customer group-specific analyses that consider income, age, cultural background, education, etc., and their correlations with actual behavior and resulting environmental potentials.

- Prospective LCA approaches could improve the representation of the SES diffusion in the future, including changes in inventories of foreground processes (e.g., ICT elements and energy technologies) and transforming background processes (e.g., products from the increasingly green basic materials industry, such as steel).

- Concerning system boundaries, the modeling of effects at the distribution grid level and the inclusion of end-of-life scenarios could result in a more complete picture of environmental effects of SESs and small-scale flexibilities.

- Modeling-wise, a hard coupling of the LCA and ESM interface could support reproducibility and address reccurring challenges. Furthermore, integrating or dedicated modeling of automation-triggered technology usage and the non-linear, differentiable expansion of power grid elements (e.g., lines, transformers) would enhance the level of detail and overall robustness of the results.

- The development of a dedicated framework or specified guidelines for the holistic LCA modelling of SESs could address still unresolved methodological challenges and support future research.

- Finally, future research could contribute to developing easy-to-apply assessment tools that enable simplified assessment of SESs, but that build on a solid LCA methodology and a robust data basis, with documented guidance for applicants. Such tools would enable a wider circle of stakeholders to conduct their own SES assessments and thereby support a broader discussion about the environmental impacts of SESs.

The environmental assessment of SESs is and remains a challenging task due to the diverse range of use cases, their pervasive nature, and the complex interrelationships among their environmental effects. The further development of methodological approaches, greater integration of empirical data, and consideration of systemic and user-related effects are key levers for better understanding and shaping the environmental effects and impacts of SESs. The challenges and solutions identified in this thesis can serve as a starting point for future research that is both scientifically sound and relevant to practice.

Chapter 6

Conclusion and recommendations

Environmental assessments support the understanding of impacts of ICT's necessary large-scale roll-out in the energy sector

The energy sector, with its transformation already underway and still ahead, is a sector that, without noticeable opposition, requires the application of ICT. Without efforts to digitalize systems, relevant energy efficiency potentials will remain untapped, and coordinating systems with high shares of intermittent renewable energy sources becomes more costly and challenging. This outlook means that stakeholders see virtually no alternative to its use, though they differ in their visions regarding depth and scale.

However, there is a greater consequence following on from this rationale. In contrast to consumer goods, the roll-out of ICT infrastructures for small-scale energy flexibilization and the services based on them are prescribed by law and accelerated through political strategies. Besides expectations regarding cost savings and improved energy system management, ICT-enabled services are being adopted to leverage environmental benefits, namely the improved integration of renewable energy sources and the reduced use of fossil energy carriers. The legal basis in Germany, the EU as a whole, and countries with similar legislation will lead to the production, operation, and disposal of several million devices, resulting in both intended and unintended positive and negative environmental effects during their use phase. However, holistic environmental assessments of such SESs and knowledge about how to conduct them are scarce. In other words, energy systems are undergoing an infrastructural transformation driven by environmental goals, but the broader environmental effects of this transformation have not yet been fully understood. On the other hand, postponing the roll-out until every detail is assessed is not an option, given the apparent benefits and the pressure to achieve climate neutrality and limit global warming to 1.5°C or 2°C, respectively, by the middle of the century.

Assessing the environmental effects of digital technologies in the energy sector and emerging technologies is a complex task due to their multi-level effects. It is further characterized by limited knowledge among researchers and industry players about the technologies' effectiveness and the methods for holistic analysis. Nevertheless, stakeholders in the energy sector's digitalization process should conduct environmental assessments. Otherwise, the intended role of digitalization and its positive effects remain mere claims and unproven, entailing a potentially undetected risk of backfire. Cost-benefit analyses or assessments that focus solely on potential benefits and narrowly drawn system boundaries are insufficient to comprehend the multi-layered effects of SESs. Furthermore, without robust environmental assessments, decision-makers may rely on overly simplified assumptions prone to preconceptions and biases, potentially leaving environmental burdens and benefits undiscovered and unexploited. Holistic environmental assessments of SESs using LCA can reveal trade-offs and opportunities for improvement – not only by identifying ways to limit burdens but also by highlighting opportunities to enhance benefits.

Establishing an environmentally sustainable digitalization process and SESs is a task requiring active efforts from industry taking product responsibility, a public articulating its expectations and representing broader interests, policy actors setting the framework conditions in the context of limited yet ever-growing knowledge and consideration of opposing interests, and research providing robust information for the understanding and directing of environmental effects.

As a contribution to this process, in this thesis I aimed to assess the environmental effects of ICT-enabled small-scale energy flexibilities as an example of SESs. For this, I chose an inter- and transdisciplinary approach that employs LCA and additional methods from economics and the social sciences.

SESs can both cause and relieve environmental issues due to optimization, behavioral, and systemic effects

On a theoretical level, I find that the environmental effects of SESs and small-scale energy flexibilities occur at and across multiple levels, interacting with each other from the local scale all the way up to the system-wide scale, resulting in potential positive and negative environmental outcomes. At the same time, direct effects from the production, operation, and disposal of SESs themselves cause negative impacts. The direction, limitability, and amplifiability of indirect effects are more open questions. In this context, three findings are of particular relevance: (1) differently than previously thought, optimization effects of SESs can lead not only to positive but also to adverse impacts, (2) optimization and usage-related effects can aggregate to systemically relevant effects such as simultaneity issues, putting additional pressure on infrastructures and, conversely, the relief thereof, or rebounds increasing power generation volumes, and (3) interactions between smart energy use cases can create synergies at the household and energy system-wide scale due to technologies' complementing characteristics. These findings are especially relevant because achieving optimization and systemic effects are the very goals of small-scale energy flexibilities and other digital applications in the energy sector. Thus, the conceptual concretization and extension of digitalization's and SESs' environmental effects may support stakeholders' future practical considerations, as well as upcoming research efforts.

Moreover, digitalization in the energy sector does not come without environmental burdens, although the results might indicate net benefits in several impact categories. These inevitable impacts should direct attention away from drawing conclusions about SESs solely on the basis of net-effect considerations, a single impact category, and individual applications. Instead, the spotlight should be directed towards the pervasive diffusion of technologies and the associated inevitable effects (such as the disposal and recycling of millions of smart metering devices and increased use of energy technologies, such as battery systems), as well as the expected burden shift towards ADPm, EPf, and ODP impacts.

LCA is a suitable approach for assessing SESs, yet it faces multiple challenges and requires complementary methods

On the methodological level, I find that LCA is a suitable approach for analyzing the environmental effects and resulting impacts of SESs. However, the characteristics of SESs pose multiple challenges for applicants – predominantly due to their currently low but expected large-scale diffusion, which causes multi-layered, non-linear effects in a system already undergoing a profound transformation.

To address questions about the environmental effects of these emerging technologies, which are inherently interdisciplinary, LCA needs to be combined with additional approaches. In the context of this thesis, integrating economic and social science methods and involving broader expert and industry insights has proven valuable for various aspects of the goal and scope definition and the inventory modeling phase. In light of (still) lacking field data for the large-scale diffusion of SESs, the coupling with established energy system models produces insightful results for the behavior of ICT-enabled energy applications in a dynamic environment. The involvement of experts facilitated the use of 'swarm' intelligence to scope and identify a range of additional methodological challenges and solution approaches. The results provided theoretical and practical knowledge, and indeed foreshadowed some of the quantitative results in the Papers summarized in chapter 4.

Besides challenges during the standard LCA phases, the thesis has shown that LCA applicants already make landmark decisions during an internal, undocumented orientation phase where guidance is particularly relevant and helpful. Although this thesis presents viable solution approaches and guidance for future LCA research, I want to reiterate that developing specific guidelines would further support this orientation phase and establish a more unified methodological basis. In particular, current and future attempts in this regard should elaborate on the multi-layered and non-linear nature of environmental effects connected with SESs and ways to assess them. Furthermore, they should explicitly point to applicable impact categories beyond the GWP as its importance decreases and the importance of at least ADPm, EPf, and ODP increase in the energy transition process.

Empirical LCA findings show that digitalization is not a silver bullet for additional decarbonization and increases other impacts

The empirical findings show that the environmental consequences of ICT for the flexibilization of small-scale energy technologies are a double-edged sword. While facilitating and improving energy systems with high shares of intermittent renewable energies and high degrees of electrification on the demand side, digitalization causes unavoidable (but limitable) direct effects and avoidable (yet amplifiable) effects that produce additional GWP impacts and a shift towards other impact categories.

Comparing more predictable effects from the life-cycle of ICT with optimization from the household and system perspective suggests that net GWP impacts are likely to be beneficial. In contrast, more ambiguous user-related effects may lead to both net reliefs and burdens if they become effective on a broad scale. In turn, net ADPm, EPf, and ODP impacts will likely result in additional burdens, regardless of the degree to which behavioral effects come into play.

However, placing numbers into a larger context shows that digitalization (or at least small-scale energy flexibilization) alone will not significantly contribute to decarbonization. On the other hand, other impacts, such as ADPm, EPf, and ODP, are less salient when viewed in the broader context of the energy system's overall environmental impacts. These contextualizations of the results suggest that the merits and issues of ICT might lie elsewhere: in the coordination of an increasingly complex energy system, in limiting costs and promoting transparency, and in addressing short-term operational challenges such as simultaneity effects.

On the other hand, although scaling and comparing results to political targets makes the results appear less relevant, this should not be taken as an invitation to neglect SESs and their environmental impacts. First, because every percentage point of additional greenhouse gas emissions reduction is a valuable step on the pathway to ultimate carbon neutrality. Second, because additional burdens should be limited and reduced in the face of the stresses that planetary boundaries increasingly face (Richardson et al., 2023; Thomassen et al., 2024).

Transferability of results to other contexts, use cases, and technologies

Looking beyond the defined scope of this thesis leads me to the following assumptions regarding the transferability of the quantitative LCA results:

- **Transferability to other geographic regions and points in time**: The application of findings beyond Germany in the points in time analyzed here (2018, 2020, 2030) should be feasible for national energy systems with similar shares of intermittent renewable generation, residual fossil-based power plants, growing electrification of the demand side, and the roll-out of digital infrastructure that enables the flexible operation of small-scale technologies. This applies, e.g., to EU countries with similar structural requirements at different points in time. However, the findings point to technical rather than socio-economic potentials. For real-life implementation, the specific regulatory framework, socio-cultural background, or economic conditions (e.g., price levels and spreads) of particular territories have to be considered. These issues, however, were not the focus of this thesis.

- **Transferability to other SES use cases based on the same technologies**: Use cases based on the same small-scale technologies most likely build on a similar ICT setup, consisting of the SM infrastructure plus parallel solutions provided by energy suppliers. Therefore, the determined impacts from the production and operation of ICT elements are eminently transferable to household-related digitalization use cases involving PVBSs, EHPs, and BEVs. Regarding indirect effects, Paper III demonstrated for a PVBS that the provision of different system services results in varying environmental impacts. Therefore, the actual use case that combines energy technology and a targeted service is decisive for the LCA result. Thus, the more general results of Papers IV (behavioral effects) and V (optimization and systemic effects) instead identify evidence for technical potential that, in the context of the applied research designs, can be considered as benchmarks for actual use cases (e.g., dynamic tariffs) based on PVBSs, EHPs, and BEVs. A significant limitation on the generalizability of the results concerns BEVs. The transferability of the directional charging use case of BEV in Paper V to upcoming bidirectional use cases is hardly possible, because of the significant change in control options from demand shift to targeted charging and discharging.

- **Transferability to other SES use cases based on different technologies**: Since SESs require the use of ICT elements, resulting impacts from direct effects of further use cases involving other technologies are probably not comparable by extent but rather by type. This means that the environmental profiles of the production of active and passive electronic components are similar, leading to at least notable ADPm, EPf, and ODP impacts. Regarding indirect effects of other household-related technologies for flexibility provision (e.g., consumer goods), it is unlikely that these technologies could result in substantial potential for flexibility because of their lower energy consumption per unit and the lack of load-shift options. This is also supported by the responses of the participating German market players to the survey in Paper II. Therefore, overcompensation of direct effects would be more challenging to achieve. Other SESs might pursue fundamentally different targets than leveraging flexibility from household-related technologies, e.g., predictive maintenance of central heating systems or simplified customer interaction via chatbots based on artificial intelligence. For these, other ICT components and indirect effects come into play that were not covered by this thesis.

In summary, the quantitative LCA results are broadly transferable to small-scale technology flexibilization in similar energy system structures. For other SES use cases based on the same or similar ICT components, impacts from direct effects are at least comparable by type. In contrast, impacts from indirect effects vary markedly across envisaged services and for other household-related flexibilities, which are less likely to overcompensate for impacts from ICT production. Transferability to other SES use cases that involve different ICT components, energy technologies, and which target fundamentally different services is not feasible.

Recommendations for improving the environmental outcome of ICT-enabled energy services

Improving the environmental performance of SESs calls for responsible management from various stakeholders. In short, the task for decision-makers is as follows: facilitating and generating likely positive effects at the system level by external control while limiting direct impacts from the production, operation, and end-of-life of ICT, carefully considering unfavorable effects on electricity consumption and energy technology use from the household perspective, and preventing rebound effects and enabling beneficial effects.

In Paper II, I argued that market players are driven by environment-oriented ambitions when offering ICT-enabled energy services, particularly when it comes to mitigating the impacts of climate change. Still, they recognize the need for further research on environmental effects and for protagonists from industry and politics to take additional measures to reduce burdens and enhance benefits. Based on the empirical findings in Paper II, I derived several options for improvement that I summarize as recommendations geared towards the energy industry and policymaking players in the following remarks:

- **Energy industry**: To limit direct effects, industry players can require sustainability standards for their own proprietary as well as external and rented server infrastructures and switch from physical to virtual energy management systems. Regarding optimization effects, they should carefully consider bidirectional charging, as this actively consumes battery load-cycles. Furthermore, they could improve tariff design to reflect current and forecasted carbon intensity and enhance control mechanisms to account for any potential negative effects related to technology use and other environmental factors. Since user behavior can result in significant environmental impacts, customer decisions should be actively supported by energy service providers offering supplementary information for configuring their energy management systems, by setting suitable default configurations (also referred to as 'adjustable green defaults' (Sintov and Schultz, 2017)), and by communicating transparently about potential effects at critical points along the customer journey. To make use of the full potential of small-scale flexibility, energy providers could pursue a "technology agnostic" policy, as one interviewee put it, meaning openness to various brands and models of technology to avoid technology lock-ins and premature disposal of devices. To increase their knowledge and contribute to robust knowledge generation, they should actively collaborate with science to test effectiveness and identify opportunities for improving SES use cases.

- **Policymaking**: Because market players tend to establish parallel communication systems due to the limited performance of the current smart metering infrastructure, regulation could provide for appropriate standards of future SM generations to avoid additional ICT expansion and usage. Furthermore, public funding schemes for battery storage systems and other technologies could require thresholds for minimum lifetimes or maximum environmental impacts. Public information campaigns and obligatory customer education by market players could support consumer decisions and raise awareness for the role of customer behavior in environmental outcomes. Existing and upcoming research programs should expand the empirical database of smart energy use cases and incentivize collaboration between science and industry to strengthen the knowledge base covering the environmental effects of these new devices and flexibilized systems. Finally, the scientific results of the environmental effects of ICT should be reflected in collaboration with market players and associations, for example through industry forums.

During the expert interviews, the respondents showed a refreshing motivation and openness to addressing environmental issues. This, therefore, constitutes a promising basis for improving the environmental outcomes of ICT-enabled energy services in the future.

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Appendix A

Publications

A.1 Contribution statements

Table A.1 Author contributions to the publications

No.	Publication, authors, contributions
I	Wohlschlager et al. (2023) – Wohlschlager, D., **Bluhm, H.**, Beucker, S., Pohl, J., and Fröhling, M.
	D. W.: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **H. B.: Conceptualization, Methodology, Investigation, Resources, Visualization, Funding acquisition, Writing – original draft, Writing – review & editing.** S. B.: Investigation, Resources, Writing – original draft, Writing – review & editing. J. P.: Investigation, Resources, Writing – original draft, Writing – review & editing. M. F.: Writing – review & editing, supervision.
II	Bluhm (2025) – **Bluhm, H.**
	Single author research article.
III	Bluhm and Gährs (2023) – **Bluhm, H.** and Gährs, S.
	H. B.: Conceptualization, Investigation, Methodology, Formal analysis, Software, Data curation, Writing – original draft. S. G.: Methodology, Investigation, Validation, Writing – original draft, Visualization, Project administration, Writing – review & editing.
IV	Ouanes et al. (2022) – Ouanes, N., Kegel, J., Wiesenthal, J., Lenk, C., **Bluhm, H.**, Weiß, J., and Torliene, L.
	N. O.: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. J. K.: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft. J. Wi.: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. C. L.: Investigation, Methodology, Formal analysis, Software, Data curation, Writing – original draft, Visualization. **H. B.: Methodology, Formal analysis, Writing – original draft, Visualization, Validation, Writing – review & editing.** J. We.: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. L. T.: Conceptualization, Writing – original draft.
V	Bluhm et al. (2026) – **Bluhm, H.**, Büttner, C., Cußmann, I., Amme, J., and Wiese, F.
	H.B.: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. C. B.: Writing – review & editing, Methodology, Investigation, Validation, Formal analysis, Software, Data curation, Conceptualization. I. C.: Writing – review & editing, Writing – original draft, Methodology, Investigation, Validation, Data curation, Conceptualization. J. A.: Validation, Formal analysis, Software, Data curation. F. W.: Writing – review & editing, Conceptualization, Supervision.

A.2 Paper I (Wohlschlager et al., 2023): Overcoming challenges in life cycle assessment of smart energy systems – A map of solution approaches

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Overcoming challenges in life cycle assessment of smart energy systems – A map of solution approaches

Daniela Wohlschlager [a,b], Hannes Bluhm [c,d,*], Severin Beucker [e], Johanna Pohl [f,g], Magnus Fröhling [b]

[a] Forschungsstelle für Energiewirtschaft (FfE), Am Blütenanger 71, 80995, München, Germany
[b] Circular Economy, Technical University of Munich (TUM), Am Essigberg 3, 94315, Straubing, Germany
[c] Institute for Ecological Economy Research (IÖW), Potsdamer Straße 105, 10785, Berlin, Germany
[d] Europa-Universität Flensburg (EUF), Auf dem Campus 1, 24943, Flensburg, Germany
[e] Borderstep Institute for Innovation and Sustainability, Clayallee 323, 14169, Berlin, Germany
[f] Technische Universität Berlin, Straße des 17. Juni 135, 10623, Berlin, Germany
[g] Zurich Knowledge Center for Sustainable Development (ZKSD), Hardstr. 235, 8050, Zürich, Germany

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ABSTRACT

Current research underlines the benefits of digitalization to integrate renewable energy sources (RES) efficiently and to coordinate generation and supply. This development towards smart energy systems (SES) includes emerging use cases at the distribution grid level, e.g., smart charging strategies for electric vehicles or energy management systems in buildings. An environmental assessment of such, however, is challenging. The standardized Life Cycle Assessment (LCA) approaches seem insufficient since SES are emerging systems at the interface of digitalization and energy with multiple intended and unintended environmental effects. This article aims to derive solution approaches for LCA professionals that investigate use cases enabled by information and communication technology (ICT), specifically in SES. To identify challenges during the first two phases of an LCA and solution approaches, we examine seven recent research projects and conduct a real-time Delphi workshop with LCA experts in the field of SES. As a result, the article provides approaches on setting up an LCA, filling data gaps, and methods to draw upon the long-term impacts of use cases in SES. Key findings include a modified taxonomy of potential environmental effects. Results show that systemic effects in SES have potentially the highest impact on the LCA, followed by effects caused by user behavior. Assessing these effects of 'higher-order' poses an increased complexity. Determined solution approaches include combining the standardized LCA with energy system modeling or surveys on user behavior. Overall, this article reveals orientation strategies and recommendations to guide LCA professionals toward a holistic environmental assessment of use cases in SES.

1. Introduction

The ambition towards climate neutrality implies fundamental changes in centralized and highly fossil-based energy systems. Information and communication technologies (ICT) in energy systems gained importance with the turn of the century, following the transformation of the energy market, power generation, and distribution in many European countries (Midttun, A. & Piccini, P. B., 2017). The increasing share of renewable energy sources (RES) poses challenges for load balancing (temporally and regionally) in the electrical transmission and distribution grid. The energy system thus has to transform from a baseload-oriented generation and distribution structure towards a system building on decentralized energy sources (Mendelevitch et al., 2018). As part of that development, electricity grids require precise information facilitated by ICT, referred to as a 'smart grid' (Tuballa and Abundo, 2016). Decarbonizing energy systems further implies the conversion of volatile RES (e.g., wind, solar, biomass) into other energy carriers than electricity (e.g., heat, biofuels, and hydrogen). Therefore, Lund et al. (2017) argue that one should instead use the term 'smart energy systems' (SES) because this represents a fundamental shift towards sector-integrated thinking for sustainable energy systems. ICT has been regarded as a prerequisite for SES, i.e., to coordinate generation and supply or to enable the integration of volatile production from RES while keeping the grid stable (Fouquet and Hippe, 2022) and thereby

* Corresponding author. Institute for Ecological Economy Research (IÖW), Potsdamer Straße 105, 10785, Berlin, Germany.
E-mail address: hannes.bluhm@ioew.de (H. Bluhm).

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advancing Sustainable Development Goal 7 (SDG 7) for universal access to affordable, reliable, and sustainable energy.

From an environmental perspective, digital devices and ICT infrastructure required in SES demand energy and resources during their life cycle. The standardized method of the Life Cycle Assessment (LCA) with its four defined phases (goal and scope definition, inventory analysis, impact assessment, and interpretation (DIN EN ISO 14040, 2006)) is often applied to assess the environmental impact of a product system (e.g., hardware devices) throughout its life cycle. However, ICT's intended and unintended impacts go beyond the technology level. For a holistic LCA-based evaluation of use cases in SES, previous assessments report increased complexity and methodological challenges, e.g., for the cases of virtual pooling of PV battery storage systems to provide energy system services (Bluhm and Gährs, 2023), smart home systems for residential energy management (Pohl et al., 2021), or smart energy metering (Wohlschlager et al., 2021).

Challenges of an LCA-based assessment of ICT already exist in the orientation phase. Because even before conducting the actual analysis, LCA professionals must first approach the SES under investigation and, if necessary, consider more specific guidelines. Further challenges occur regarding the goal and scope, e.g., the definition of the functional units (FU), or system boundaries. As for the inventory analysis, an exemplary issue is insufficient access to data on ICT. Consequently, system boundaries are often set too narrowly by LCA professionals, leading to neglecting specific environmental impacts (Arushanyan et al., 2014). Additional challenges are related to the early market penetration of ICT-enabled use cases in SES, thus representing emerging technologies with immature product systems and a deployment depending on future decisions in a changing, dynamic technical context (Miller and Keoleian, 2015). Emerging technologies are typically assessed through a prospective LCA (pLCA), which involves challenges regarding comparability, careful data collection, consideration of uncertainty (Thonemann et al., 2020), and missing standardized methods in this field (Fröhling and Hiete, 2020).

Existing LCA-based investigations of ICT identify the above-mentioned challenges. To the best of the author's knowledge, however, a comprehensive overview of obstacles along the phases of an LCA and respective solution approaches when assessing use cases in SES is still lacking. Built upon this research gap, this article aims to answer the overall research question: *What methodological challenges occur for LCA professionals when assessing the environmental effects of ICT-enabled use cases in smart energy systems, and what are appropriate solutions?* To answer this question, the article addresses four guiding questions that focus on the first two phases of an LCA, i.e., the methodological setup, as follows:

1. What should be considered when setting the playing field of the LCA?
2. How to define the goal and scope elements?
3. How to collect data for the life cycle inventory phase, and how to address missing data?
4. How to consider future developments of the technical systems involved?

The article is structured in six sections. Section 2 provides an overview of ICT-enabled use cases in SES and a modified taxonomy of potentially associated positive and negative environmental consequences. The article applies a two-step methodological approach to derive empirical findings on the four guiding questions (Section 3). First, recommendations to determine environmental effects caused by use cases in SES are generated through the evaluation of research projects that conduct an LCA-based assessment of such. Secondly, a real-time Delphi serves to supplement these findings with expertise from LCA professionals working in the field of ICT and SES. Detailed empirical findings are summarized (Section 4) and critically reflected (Section 5). The article closes with recommendations for future assessments in Section 6.

2. Background

2.1. Use cases in the smart energy system

In recent decades, ICT has already been used to monitor and control the conventional energy system (Weigel et al., 2021). Besides new use cases for grid operators and energy suppliers, ICT enables additional applications for end consumers such as private households (Weigel and Fischedick, 2019). According to a basic definition, a use case can be understood as a scenario describing the process and application of achieving a specific goal, for a specific stakeholder with a particular solution or technology (Cockburn, 2001).

An application-oriented categorization of use cases in SES is provided by Weigel and Fischedick (2019). The authors carry out a literature review on digital applications in the energy sector based on ten publications covering different technologies and steps of the value chain. Applications are subdivided into three main and seven sub-categories of use cases:

- System balance: applications designed to secure the energy system's operation, including use cases from 1) smart grid and optimized operation, 2) smart market and flexibility integration, and 3) anomaly identification and predictions
- Process optimization: increased efficiency and/or quality of internal processes also covering use cases from 3) anomaly identification and predictions, and 4) process efficiency
- Customer orientation: provide additional services or value for clients covering use cases from 5) smart energy management of buildings, 6) communication channels, and 7) trust and transparency

We use the sub-categories by Weigel and Fischedick (2019) in Section 3.1 to classify the investigated use cases of evaluated research projects.

2.2. Environmental effects of use cases in smart energy systems

Environmental effects of ICT include both intended benefits and unintended side effects (Coroamă et al., 2020). To categorize these effects, Berkhout and Hertin (2001) introduced a taxonomy that differentiates between effects on different levels, further developed over the last decades. As outlined in a review by Horner et al. (2016), an established categorization is the differentiation between effects of 'first-order' (direct effects) and 'higher-order' (indirect effects). First-order effects have a resource-increasing (i.e., 'negative') impact and result from the footprint of ICT hardware along the product life cycle. Higher-order effects comprise impacts from the ICT application beyond the product life cycle of ICT hardware, including both intended benefits and unintended side effects (Coroamă et al., 2020). While Hilty (2008) already distinguished environmental effects related to technology, application, and behavior & structure, Pohl et al. (2019) enhanced the differentiation within taxonomies by assigning effects to three levels: the 'technology', 'user', and 'system' level. While first-order effects only apply on the technology level (i.e., the ICT's footprint), higher-order effects may occur on all three levels (compare Fig. 1).

Intended higher-order effects on the technology level include 'substitution' and 'optimization' (Pohl et al., 2019). Substitution effects arise from exchanging types of products by their digital equivalents. They can lead both to a reduced or, in cases where the digital equivalent comes with higher resource demand, increased environmental impact. Optimization effects stem from reduced impact through optimizing a process by providing information (e.g., more efficient monitoring of electricity consumption through smart meters). Numerous use cases in SES target the achievement of this effect (Pohl et al., 2019).

The 'user' level defines environmental effects through behavioral changes caused by the introduction of ICT (Pohl et al., 2019). First, the 'rebound effect' occurs due to efficiency gains and resulting financial or

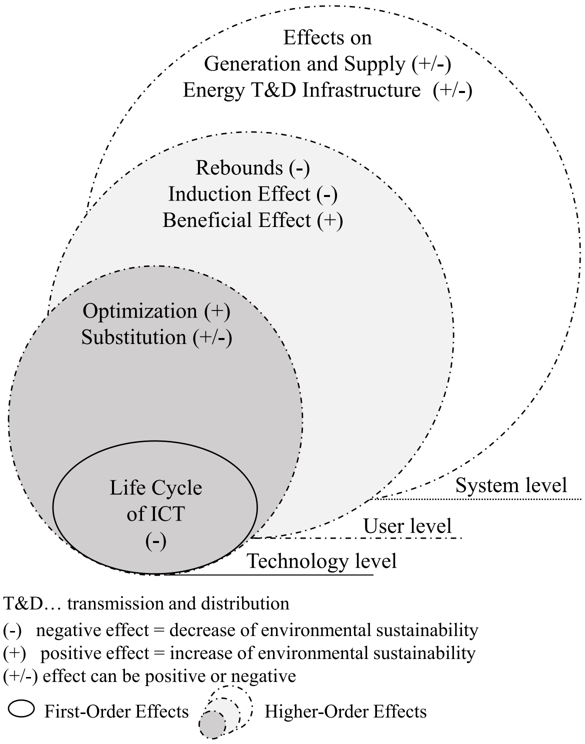

Fig. 1. Environmental effects of ICT on different levels, applied for SES (modified after Pohl et al. (2019)).

time savings (Sorrell, 2009). In this article, we define 'rebound effects', short 'rebounds', as negative effects due to efficiency gains and resulting financial or time savings gained through ICT (Gossart, 2015). Secondly, 'induction effects' also lead to an increased impact due to user behavior, attributable to an increased choice of options (Walnum and Andrae, 2016). Examples include increased usage of ICT devices because of the overall higher availability of such devices (Pohl et al., 2019). This article covers positive behavioral effects under the term 'beneficial effects' (see Santarius and Soland, 2018).

From the 'system' perspective, literature discusses the effects on the overall economy or society (cf. review by Horner et al. (2016)). In this article, 'system' refers to the energy system with an investigation of two key effects. First, effects on transmission and distribution (T&D) infrastructures ('Energy T&D Infrastructure') describe repercussions caused by ICT-enabled use cases on conventional energy infrastructures (e.g., grid lines). For example, smart charging strategies of battery electric vehicles (BEVs) as a use case include changing reinforcement requirements of electricity grids due to a shift of peak loads (Müller et al., 2022). Effects on 'Generation and Supply' include changes in RES integration, e.g., impacting the emission factor of electricity generation depending on the charging strategy Xu et al. (2020).

Fig. 1 provides an overview of the environmental effects of ICT, specifically within SES. Table 1 includes exemplary effects of use cases evaluated in this article. Although new use cases could cause implications beyond these two systemic effects, we consider the choice as an appropriate focus of this study by encompassing the main components of energy systems. Previous investigations faced several challenges in determining effects on all levels. To derive solutions approaches for a holistic assessment, this article provides conclusions on empirical findings as outlined in Section 4.

3. Methods

The article applies a two-step methodological approach. First, we evaluated research projects that include an environmental assessment of use cases in SES. Secondly, we elaborated on identified challenges and solution approaches with LCA professionals in a real-time Delphi. The research design follows the four guiding questions outlined in Section 1 to gather empirical findings on these methodological challenges within the LCA.

3.1. *Evaluation of research projects*

A case study approach derives an empirical basis for challenges and solutions for LCAs on SES. For this, seven research projects are evaluated (see Table 2). The case study selection represents a sample, meaning that the choice is based on practical criteria instead of pursuing representativeness (Etikan, 2016). The central criterion is the thematic orientation, i.e., the LCA-based investigation of ICT-enabled use cases specifically in SES. For comparability between projects, the focused categories of use cases cover those on a decentralized energy system level, thus applied by small-scale end consumers (e.g., households) and with a geographical scope in Germany. However, the goal and scope elements reveal different methodological approaches, e.g., for the FU (per unit or scaled to entire energy systems) or the choice of impact categories (from single categories up to category sets). The authors of this article or institutional colleagues are involved in conducting the projects studied, allowing detailed access to challenges and solution approaches that are usually outside the scope of scientific publications. Besides available publications, the experiences of the project members thus serve as empirical sources.

All analyzed projects are publicly funded and conducted by various independent research institutions. The assessments cover the effects of first- and higher-order (cf. Section 2.2), different choices on the impact categories, coping with multi-functionality, and the overall LCA approach. In this regard, attributional LCA (ALCA) assumes a static technical sphere that is based on actual, forecasted, average or generic foreground and background data. A consequential (CLCA) approach considers theoretical dynamics between the analyzed system with markets, policies, and consumer behavior (EC et al., 2010).

3.2. *Real-time delphi*

By applying the survey format of a real-time Delphi, LCA professionals participated in an online workshop. The format is chosen for the article since it enables an efficient discussion and reflection with experts and elaborates solutions to identified problems (Gerhold, 2019).

For this analysis, sixteen LCA experts with experience in evaluating use cases in SES from different organizational backgrounds (see Table 3) actively participated in a real-time Delphi.

The Delphi covered two interactive parts. First, a survey addressed the previously identified environmental effects on the technology, user, and system level (see Section 2). For each effect, participants ranked the potential impact on the LCA result as well as the level of difficulty to assess. A predefined scheme located the ranked effects into four quadrants (see Fig. 2). Following the real-time Delphi approach, participants built on their experience of a hypothetical use case and reacted to interim survey results. Participants could leave single effects unanswered and edit their responses. The results in Section 4.2, thus, represent a consensus among the participants. Secondly, participants elaborated upon challenges and solution approaches concerning the four guiding questions (see Section 1) in a moderated discussion format. The supplementary material provides details on the findings.

4. Results

The following Section outlines the key findings from the two

Table 1
Modified taxonomy of environmental effects of ICT within SES.

Level	Technology Level			User Level			System Level	
Category	First-Order	Higher-Order						
Effect	Life cycle of ICT	Optimization	Substitution	Rebounds	Beneficial Effects	Induction Effects	Energy T&D Infrastructure	Generation and Supply
Impact	(−)	(+)	(+/−)	(−)	(+)	(−)	(+/−)	(+/−)
Description of effects	Energy and resource demand for production, operation, and end-of-life management of ICT	Efficiency improvement of conventional products/ processes and thus less energy and resource use	Replacement of conventional products/ processes by ICT that poses a higher/lower lifecycle-based footprint	Increased demand resulting from efficiency gains and thus higher purchasing power or more available time	Reduced demand for a specific technology due to increased information or improved control over frugal use	Increased/ reduced demand not attributable to efficiency gains but to a higher choice of options or transparency on information	Repercussions on energy T&D infrastructures increase/decrease the requirement for expansion or reinforcements	Impacts on the merit order of power generation, dispatch measures, or storage facilities
Example: smart charging of BEVs compared to uncontrolled charging	Energy and resource demand of digital devices and ICT infrastructure required for smart charging	Charging in times of low GHG emissions and thus lower operational emissions of BEV	No substitution impact	Increased driving or demand for other goods due to financial savings from smart charging strategies	Information on charging emissions lead to an adoption of charging behavior in times of high RE availability	Availability of apps to control charging processes leads to higher usage of digital devices	Higher/lower charging simultaneities increase/decrease requirements of electricity grid expansion	Higher/lower integration of RE or replacement of large-scale battery storage by bidirectional BEVs as decentralized options
Example: Smart metering compared to analog metering	Energy and resource demand of devices, data transfer, operator's infrastructure, customer portal usage	No optimization impact	Substitution of traveling for on-site meter read-out	Replaced household appliances as a result of monitoring are more energy efficient but potentially larger	Potential subsequent replacement of inefficient household appliances due to increased information	Availability of apps for load monitoring leads to higher usage of digital devices	Lower energy consumption by household appliances decreases requirements for electricity grid expansion	Lower energy consumption decreases overall electricity generation needs

(−) … negative effect = increase of environmental impact, (+) … positive effect = decrease of environmental impact, (±) … effect can be both positive or negative; T&D … transmission and distribution.

methodological steps (evaluation of research projects and Delphi) along with the four guiding questions of the article (see Section 1). The supplementary material of this article provides detailed results from both approaches.

4.1. Setting the playing field of the LCA

Setting the playing field of an LCA on SES use cases is complex. Researchers of the investigated projects and Delphi participants faced various colliding factors: e.g., stipulations of formal LCA guidelines professionals try to follow, the intention of assessing first and higher-order effects, the definition of the use case within a specific context, or the consideration of the characteristics of energy systems and markets. Table 4 summarizes derived solution approaches.

Delphi participants recommend mapping the LCA's stakeholders and involving them in the research process to produce results more tailored to target groups, as conducted in some analyzed projects. Participants highlight being careful to maintain neutrality and address stakeholders with different perspectives on the use case when defining the research question and case study. Consumers as stakeholders, e.g., expect transparent technology impact assessments covering potential up- and downsides at all levels, including societal and economic aspects.

Furthermore, investigated projects make use of general or ICT-focused LCA guidelines. Especially in the context of SES, however, Delphi participants regard existing guidelines as insufficient, e.g., to address higher-order effects or other aspects such as the choice of impact categories. Therefore, there remains a gap in tailored guidelines for SES use cases at the interface of ICT and the energy system. To build case studies, both investigated projects and Delphi participants apply use case classification schemes, thematic industry standards, specific frameworks, meta-studies, and consider the energy "data landscape".

4.2. Defining goal and scope elements

The definition of the key goal and scope elements of LCAs on SES use cases can be challenging due to limited guidance and experience. Thus, becoming aware of working options for defining these elements, as summarized in Table 5, helps the decision process.

Starting with the overall goal, Delphi participants discussed the varying interests of LCA professionals – while manufacturers are more concerned with the ICT life cycle, researchers might instead focus on the strategic role of SES in the energy system and its transition to a system with 100% RES. Since use cases in SES primarily provide new services, defining the reference product system is particularly challenging. Investigated projects compare SES with analog and less advanced systems and use multiple reference systems.

Since analyzing the environmental effects of SES at different levels is linked to the definition of system boundaries, professionals must decide what effects are relevant for the particular use case. Fig. 2 outlines the ranking of identified effects conducted in the Delphi workshop. LCA professionals face limited resources when conducting an LCA and must appropriately manage the depth of their analyses (data acquisition etc. (cf. EC et al., 2010). Therefore, we suggest generic research recommendations for each quadrant (Q). The experts at the Delphi workshop endorsed the following recommendations:

- QI *'No rocket science'* – low to medium impact, low to medium challenge: If a holistic LCA considering higher-order effects is to be performed, LCA professionals should pay lower attention (compared

Table 2
Overview of evaluated research projects.

Project Metadata			Product system			Goal and scope						Publi-cations
						Modelled year(s)	FU	Assessed effects			Impact categories[b]/LCA approach/multi-functionality	
No.	Name	Dura-tion	SES use case	Sub-category[a]	Reference			Technology	User	System		
1	Climate Protection Potential of Digitalization	2019 2021	Smart metering with non-intrusive load monitoring (NILM)	Smart energy management of buildings	Analog metering	2018, 2030	Annual single-family household's electricity consumption (scaled)	• LCA of ICT • Substitution • Optimization	• Beneficial	• Energy T&D Infrastructure	GWP, CED (+5 categories in Bluhm and Gährs (2023))/ALCA/system expansion	Gährs et al. (2021), Bluhm and Gährs (2023)
			PV battery storage as part of a virtual power plant	Smart market & flexibility integration	PV battery storage w/o being part of virtual power plant				• Beneficial	• Generation and Supply • Energy T&D Infrastructure		
			Flexible operation of heat pumps and electric charging stations	Smart grid & optimized operation	Non-flexible operation of heat pumps and charging stations			• LCA of ICT • Optimization	–	• Generation and Supply • Energy T&D Infrastructure		
			Weather forecast control of heating systems	Anomaly identification & predictions	Heating w/o weather forecast control		Annual multi-family household's gas consumption (scaled)		• Rebound	–		
			Online efficiency monitoring of heating systems	Process efficiency	Heating w/o online efficiency monitoring				• Beneficial • Rebound	–		
2	DETECTIVE – Energy saving through digitalization	2020–2022	Smart metering with NILM	Smart energy management of buildings	Analog metering	2020	Annual single-family household's electricity consumption (scaled)	• LCA of ICT • Optimization	• Beneficial • Rebound	–	GWP/ALCA/-	Aretz et al. (2022)
			Online efficiency monitoring of heating systems	Process efficiency	Heating w/o online efficiency monitoring		Annual multi-family household's gas consumption (scaled)	• LCA of ICT • Optimization	• Beneficial	–		
3	C/sells	2017–2021	Decentralized flexibility market platform via smart meter infrastructure	Smart market & flexibility integration	Metering infrastructure of a consumer and prosumer	2020–2030	Annual impact of ICT infrastructure required for flexibility provision from a PV system per household (scaled)	• LCA of ICT • Substitution	–	–	GWP/ALCA/-	Wohlschlager et al. (2021)
4	BCM - Bidirectional Charging Management	2019–2022	Bidirectional charging of battery electric vehicles	Smart market & flexibility integration	Conventional (uncontrolled) charging of BEVs	2019–2040	Annual charging of a household's BEV with 60 kWh battery capacity (scaled)	• LCA of ICT • Optimization	–	• Generation and Supply	GWP/ALCA, pLCA/-	Wohlschlager et al. (2022)

(continued on next page)

Table 2 (*continued*)

Project Metadata			Product system			Goal and scope						Publi-cations
						Modelled year(s)	FU	Assessed effects			Impact categories[b]/LCA approach/multi-functionality	
No.	Name	Dura-tion	SES use case	Sub-category[a]	Reference			Technology	User	System		
5	unIT-e^2 - Living lab for integrated e-mobility	2021–2024	Bidirectional charging of battery electric vehicles	Smart market & flexibility integration	Conventional (uncontrolled) charging of BEVs	2025–2050	Annual charging of a household's BEV with 60 kWh battery capacity (scaled)	• Optimization	–	• Generation and Supply • Energy T&D Infrastructure	GWP/ALCA, pLCA/-	Ostermann et al. (2022)
6	Digitalization and Sustainability (Subproject Smart Home Systems)	2016–2022	Energy Management with Smart Home Systems in Germany	Smart energy management of buildings	Different energy-saving scenarios of smart heating	2019/2020	Study 1: Managed apartment space for 5 years (scaled)	• LCA of ICT • Optimization	• Induction effect • Rebound • Beneficial	–	Study 1: GWP, PED, ADP, Ecotox/ALCA/ customized approach	Pohl et al., 2021
							Study 2: Annual provision of energy management in a residence per resident (per unit)				Study 2: GWP, MDP/ ALCA/customized approach	Pohl et al., 2022
7	Green Technology Choices	2013–2015	Demand-side energy management using Building Energy Management Systems (BEMS)	Smart energy management of buildings	Natural gas or electricity to provide space heating in unmanaged buildings	2010, 2030, 2050	Annual energy savings in managed building space (per unit)	• LCA of ICT • Optimization	• Rebound	• Generation and Supply	15 impact categories (ReCiPe 2008; cf. Goedkoop et al., 2013)/ALCA, pLCA/-	Beucker et al. (2016)

[a] Assigned to a suitable sub-category as defined by Weigel and Fischedick (2019), cf. Section 2.1.
[b] Impact categories: ADP … abiotic depletion potential; CED … cumulative energy demand; Ecotox … ecotoxicity; GWP … global warming potential; MDP … mineral resource depletion; PED … primary energy demand.

Table 3
Participants of the delphi.

Organizational background	No. of experts
Research (Energy Engineering, Environmental Engineering, Computer Science)	11[a]
Consulting	2
Industry	2
Municipal utility	1
	Σ = *16*

[a] Including four authors of this article.

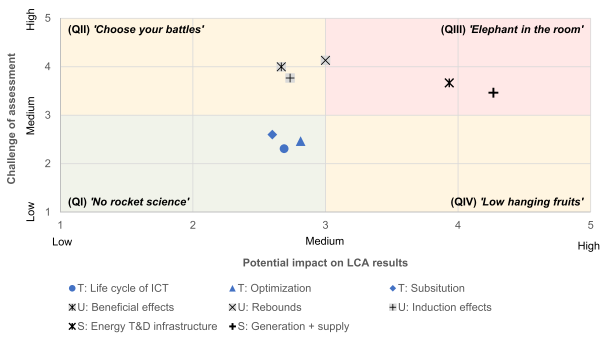

Fig. 2. Ranking of environmental effects based on potential impact and challenge of assessment resulting from the Delphi (T = Technology; U = User; S = System).

Table 4
Challenges and approaches when setting the playing field of the LCA.

Challenge	Solution approach (examples in parenthesis)
Lack of orientation when setting up an LCA on SES	Mapping the LCA's stakeholders and involving stakeholders in the research process (contractee, external stakeholders like grid operators, consumers, or via project advisory board) Make use of: • general guidelines (ISO 14040, ISO/TR 14049:2012, ILCD handbook (EC et al., 2010) • ICT-specific guidelines (e.g., ETSI, 2015; ITU-T, 2015) • use case classification schemes for SES (Weigel and Fischedick (2019) for digital energy applications in general, or Ostermann et al. (2022) for smart charging use cases) • industry standards (EN 15232 for building management systems) • existing frameworks (environmental effects (see Section 2.2), integrating specific effects like user behavior (Pohl et al., 2021)) • energy "data landscape" (consumer statistics on electricity and heating, monitoring reports by regulatory bodies, census on buildings and housing) • meta analyses (Arushanyan et al. (2014) for LCAs on ICT products and sevices, or Pohl et al. (2019) for analyses assessing indirect effects)

to effects in other quadrants), spend fewer resources, and may – where justified – carry out simplified approaches.

- QII '*Choose your battles*' – low to medium impact, medium to high challenge: Professionals should pay higher attention than QI. Given the high assessment challenge, one can justify focusing on single effects while deliberately excluding others.
- QIII '*Elephant in the room*' – medium to high impact, medium to high challenge: Professionals should pay the greatest attention. Given the high assessment challenge, one can justify focusing on single effects.

Table 5
Options for the definition of goal and scope elements.

Challenge (Definition of …)		Solution approach (examples in parenthesis)
Goal	–	Physical product improvement of digital devices (materials of smart meter) Strategic decision-making on the role of SES use case in energy system
Reference system	Technical system	No reference due to missing current comparison Analog equivalent or digital but less developed system
	Diversity	Single reference (one fossil heating system) Various references/scenarios (several fossil heating systems)
System boundaries	Technology User System	See Section 2.2 and Fig. 2.
FU	Service	Specific (energy) unit (electricity consumption for charging per kilometer of driving) Scaled energy unit/system (annual electricity consumption for charging one BEV) Technical infrastructure (charging infrastructure for one BEV)
	Time	Per annum Multiannual (5 years)
Time reference	Direction	Documented time interval (past or recent years) Future years (single or several years up to 2050)
	Resolution for energy mixes	Annual averages Interannual (hourly, quarter hour)
Geographic reference	Diversity	Single country Various countries or regions (IEA regions)
Inventory modeling approach	Technical sphere	Static (ALCA using average energy mixes) Dynamic (CLCA with single marginal generation technology or mix of technologies)
	Product	Static characteristics Changing characteristics (pLCA, see Section 4.4)
Handling of multi-output	–	No co-products or neglect System expansion (energy system services) Customized approach based on ISO/TR 14049 (2012)
Impact categories	Diversity	Typically applied for energy (GWP, CED) Relevant for energy and digitalization (additionally ADP or ecotoxicity, see Schödwell and Zarnekow (2018)) Broad indicator sets of impacts assessment method (ReCiPe 2008; cf. Goedkoop et al., 2013)

- QIV '*Low hanging fruits*' – medium to high impact, low to medium challenge: Professionals should conduct a full assessment if sufficient resources are available.

While results show a clear difference in the potential impacts and challenges to assess between the technology, user, and system level, Delphi workshop participants see a low difference in effects within the same level. While participants regard effects on the technology level as comparatively easiest to assess with the lowest impact *('no rocket science')*, effects on the user (*'choose your battles'*) and system level (*'elephant in the room')* pose a comparatively higher challenge. The participants reasoned that assessing those involves interdisciplinary methods. None of the effects are regarded as *'low hanging fruits'*, highlighting the need for further methodological guidance regarding LCA-based assessments in SES.

Regarding the FU, LCA professionals in our study model data and impacts related to specific units (primarily energy units) or scaled units/ systems. Unit approaches facilitate comparisons to other case studies with the same FU suggesting linear relations between inventories and results, while scaled units inform about the absolute impacts of the system in its defined context at the cost of difficulties in the comparability of use cases. Delphi participants further discuss that geographic and temporal references define the granularity of the analysis. It is also linked to the required inventory data (based on secured historical data or assumptions about the future) and the inventory modeling approach. Analyzed projects typically involve ALCA approaches. Delphi participants highlight the need for CLCA approaches in further investigations to consider future dynamics of the SES and the surrounding technical sphere (see Section 4.4). In investigated projects, co-products or services are either neglected or assessed using system expansion to address multi-outputs in the LCA. For the impact assessment, categories of choice are either focused on impacts triggered by generation and consumption, by digital devices, or whole indicator sets.

4.3. Data collection and addressing data gaps

Several challenges concern data gathering, as outlined in Table 6. LCA professionals in our study emphasize limited access to LCI data on ICT and data to determine the effects of higher-order. Next, they faced outdated and unspecific data sets when using common LCI databases. Analyzed projects use publicly available technical data, e.g., on weight or power consumption of components, input from expert interviews, or with secondary empirical data. Our analyzed projects use or create generic models for ICT hardware or a specific device to complement missing data, serving as a proxy for remaining ICT devices. Some studied projects use measurements (e.g., to model the operation phase) while others use energy system modeling (e.g., on a household level).

As there is limited representative data on user behavior for novel use cases in SES, analyzed projects often exclude variances in usage behavior. Professionals either model usage scenarios via secondary data or collect primary data to close this gap. Delphi participants discussed that online surveys reach more respondents and are comparatively time and cost-efficient, but only serve to collect self-reported behavior. Some investigated projects use measurements (e.g., within filed trails) to derive actual data on electricity consumption. Similarly, data collection is complex for systemic effects, yet the evaluation is highly important for outcomes (see Fig. 2). LCA professionals in our study faced limitations, including working with annual averages or focusing on single systemic effects (e.g., distribution grid) without interactions with other levels of the energy system (e.g., transmission grid). In analyzed projects, missing data is either derived from modeling or simulations based on scenarios, sensitivity analyses, the determination of a break-even (e.g., minimum reductions of grid expansion that compensate for first-order effects), or qualitative discussions.

For data validation, Delphi participants suggest external critical reflection with ICT or interdisciplinary experts and uncertainty analysis (e.g., on the representativeness of the user group regarding behavioral data). When applying secondary data, participants consider possible limitations and transferability to the analyzed use case compared to the underlying methodology and assumptions of secondary data.

Table 6
Challenges and approaches to data collection and addressing missing data.

Challenge	Solution approach (example in parenthesis)
Insufficient and outdated data to model technology level	Publicly available technical data (manufacturers) or other empirical secondary data Expert interviews (manufacturers) Definition of generic model as a proxy Own data measurement in pilots (electricity consumption, data transmission) Energy system modeling (on household level)
Lacking consideration of user parameters	Modeling of usage scenarios using secondary data (customer or panel data) Collecting primary data (surveys, measurements) Usage of secondary customer or panel data Uncertainty analysis (ensuring representativeness)
Lacking consideration of systemic effects	Energy system modeling (national energy system) Break-even calculations Sensitivity analyses Qualitative discussions
Data validation	External critical reflection Uncertainty analysis Compatibility of underlying method & assumptions of secondary data to use case

4.4. Considering future developments

Lastly, Table 7 provides the resulting approaches regarding the consideration of future developments in the LCA. Since the upscaling pathway of use cases in SES is unknown, Delphi participants recommend developing scenarios with interdisciplinary experts or using existing scenarios from the literature. Delphi participants emphasized on market developments and changing policies, which some of the investigated projects considered. Next to the unknown diffusion of hardware, LCA professionals face challenges when modeling data transmission and storage scenarios since technical standards are under development and potentially change. Approaches applied in investigated projects include calculations based on current standards and sensitivity analyses in data-intense use cases.

To consider future developments in LCI data, Delphi participants recommend using future-oriented secondary data, e.g., available pLCI databases, as also applied in some investigated projects. Assuming future scenarios in renewable-based SES with a declining carbon intensity of electricity, Delphi participants further highlight the need to shift the focus from the operation to the production phase and expand the chosen impact categories beyond the global warming potential (GWP). Some analyzed projects include additional categories, e.g., Abiotic Depletion Potential (ADP).

To assess effects within the overall energy system and, thus, dynamics and non-linear impacts of the applications' diffusion, analyzed projects recommend conducting a CLCA with modeling methods. For example, energy system models or simulations determine the

Table 7
Challenges and approaches in considering future developments of the technical systems involved.

Challenge	Solution approach (example in parenthesis)
Unknown upscaling pathway/ diffusion of technology	Scenario development with interdisciplinary experts or application of scenarios from literature Considering developments of markets and policies Considering changing standards for data processing
Data collection considering future developments	Using future-oriented secondary data (LCI data, behavioral effects) Application of available pLCI databases ('THEMIS' (Gibon et al., 2015), 'wurst' (Mutel and Cox, 2022), 'premise' (Sacchi et al., 2022), 'superstructure-approach' (Steubing and de Koning, 2021))
Shift of relevance regarding LCA phases and environmental impacts	Shifting the focus to most relevant LCA phases in future years Expanding set of chosen impact categories (Abiotic Depletion Potential (ADP), Ecotoxicity (Ecotox))
Consideration of dynamics between SES and technical sphere	Conducting CLCA by using modeling methods (energy system models, simulations on T&D infrastructures)

repercussions of SES use cases on emission factors of electricity generation or grid expansion needs. Results can serve as input for the LCA-based assessment, as also recommended by Delphi participants.

5. Discussion

In the following, we reflect on our core findings about our research questions and contextualize them in scientific literature. A critical reflection of the limitations of the chosen methods and conclusions for future research on LCA-based assessments of use cases in SES follows this.

1. What should be considered when setting the playing field of the LCA?

The orientation phase of an LCA requires landmark decisions for further investigations. In any LCA, professionals can consult external stakeholders when setting the playing field of the analysis and use more specific literature and guidelines. However, there are still few SES use cases, so specialized guidance is limited. Since the orientation phase is not one of the four standard steps in LCA, there is only rather general scientific literature available on this research question (e.g., EC et al., 2010), and some meta-studies reporting on the lessons learned for ICT-related LCAs in general (e.g., Arushanyan et al., 2014; Pohl et al., 2019). For assessing use cases in SES in particular, Gährs et al. (2021) list several similar but less comprehensive approaches compared to those we identified from the research projects and Delphi workshop. Our findings thus guide professionals for this first step.

2. How to define the goal and scope elements?

There is a large spectrum of options for defining the goal and scope elements as the first standard step in LCAs. Potential choices for digital systems have been discussed in several studies. E.g., Pohl et al. (2019) and Arushanyan et al. (2014) provide meta-studies of LCAs on ICT-related services and discuss common goal and scope definitions, especially regarding the assessment of higher-order environmental effects. Van der Giesen et al. (2020) and Jones et al. (2017) discuss goal and scope options for emerging technologies and distributed electricity generation. In this article, we present options for LCAs, specifically in SES. By deriving empirical findings from analyzed research projects and a Delphi workshop, our results expand those solution approaches of existing literature. Although our results are partly confirmed by the literature, not all potential goal and scope options for LCAs on digital systems are applied to assess SES so far.

3. How to collect data for the life cycle inventory phase and how to address missing data?

Collecting inventory data and addressing missing data remains a challenge for SES due to the emerging character of the product systems. Regarding the technology level, the identified issue of outdated datasets in common LCI databases is also known for ICT in general (Clément et al., 2020). Approaches applied in investigated research projects range from using generic data to primary data collection. Participants in the Delphi agreed that data quality and effort for data collection depend on the objective of the LCA. If a holistic analysis with indirect effects is aimed for, simplification to model the technology level and thus using generic data is acceptable (see Section 4.2). Primary data collection, however, is specifically relevant regarding the effects of higher-order. Methods for the primary data collection on user behavior for ICT applications are summarized by Pohl et al. (2019). Because of ICT's emerging character in SES, guaranteeing representativeness and data validation remains a challenge. Thus, some investigated research projects apply surveys or measurements as part of a case study approach. Data collection to model the system level is even more challenging and represents an '*elephant in the room*'. Derived strategies from LCA professionals include using the output of techno-economic simulations by combining LCA with energy system analysis. The literature outlines methodological approaches for such a combination (e.g., Betten et al., 2020). For all effects, our empirical findings show that data validation is crucial.

4. How to consider future developments of the technical systems involved?

To model future impacts, results show systemic developments within the energy system, e.g., changing markets or policies, and ICT-specific changes such as those of technical standards need consideration. Here, the early market penetration phase poses a main challenge when using cases in SES, leading to undefined and rapidly changing standards. One approach is to develop and test scenarios with interdisciplinary experts. A future-oriented adjustment of data is possible by applying available pLCI databases. Among others, the most recent efforts include the open-source tool 'premise' by Sacchi et al. (2022). Lastly, a CLCA approach that involves techno-economic modeling of the energy system is recommended to consider systemic effects of future SES. Literature shows that sophisticated CLCA methods combined with energy system models can lead to vastly different results than ALCA (Lund et al., 2010). Several methodological approaches to combine LCA and energy system analysis for CLCA modelling have been developed (see Le Luu et al., 2020). For the example of impacts caused by smart charging strategies of BEVs, Xu et al. (2020) considered different charging strategies in an energy system model.

5.1. *Critical reflection*

The article provides several research recommendations to combat challenges when assessing different environmental effects of SES. To decrease complexity, we aggregate multiple environmental effects on the technology, user, and system levels into a few key effects. The discussed effects, thus, are not exhaustive but cover a broad spectrum of potential environmental consequences.

Regarding the methodology, the selected Delphi participants cover experts from different stakeholder groups to include diverse perspectives. The reader should be aware that the limited number and the distribution of professional backgrounds of participants as well as the analyzed research projects, however, are not representative. Although the results may not present a complete picture of all potential challenges and solution approaches, the article provides guidance in this complex field of research. While Delphi participants agreed to the generic research recommendations, they pointed out that each case study has to be viewed in its specific context and in alignment with the research question. This sets forth the limitations of applying the recommendations as "one-fits-all solutions".

In this article, we have identified possible practices without evaluating how expediently or efficiently these approaches solve a specific problem compared to other methodological approaches. As the transformation towards SES progresses, one can expect more substantial attention from LCA professionals toward these systems and analyses to be carried out. Therefore, future research can build upon this work and reveal further insights via case studies on SES or by conducting more extensive, standardized surveys among LCA professionals.

Although the article investigates obstacles of LCA in SES, certain challenges (e.g., assessing high-order effect or missing data) are, however, omnipresent in any LCA. Thus, the article not only provides tailored guidance for the SES-specific challenges, but also offers starting points for mitigating or managing universal challenges for LCAs outside the scope of SES.

6. Conclusions

The role of ICT gained importance with the ongoing transformation of the conventional energy system towards a smart system based on RES. Environmental effects associated with novel use cases can occur at the technology, user, and system level. Defining the conceptual basis for a life-cycle-based assessment, collecting data, and addressing future developments are challenging tasks. Although some environmental assessments have been carried out on use cases in SES, an overview of obstacles and respective approaches is lacking. To contribute to this research gap, this article outlines methodological challenges and solution approaches derived from seven recent research projects and a real-time Delphi workshop. Our empirical findings reveal that general LCA guidelines are insufficient for assessing SES and that LCA professionals apply different strategies before and during the analysis. Results show that evaluating higher-order effects at the user and system level today and in the future requires the combination of the standardized product-oriented LCA with interdisciplinary approaches, e.g., from social sciences and energy system modeling. Future developments of the product system and its technical sphere need to be addressed. In so doing, professionals can plan their analysis and resources by using the generic research recommendations we have identified in conjunction with each type of effect. Thus, our results reveal orientation strategies explicitly for LCAs on SES use cases that have not been discussed in this depth and specificity thus far. LCA professionals can use the derived recommendations of this article as a map of options for further assessments.

CRediT authorship contribution statement

Daniela Wohlschlager: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Hannes Bluhm:** Conceptualization, Methodology, Investigation, Resources, Visualization, Funding acquisition, Writing - original draft, Writing - review & editing. **Severin Beucker:** Investigation, Resources, Writing – original draft, Writing – review & editing. **Johanna Pohl:** Investigation, Resources, Writing – original draft, Writing – review & editing. **Magnus Fröhling:** Writing – review & editing, 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.

Data availability

Empirical data (qualitatively) dervied for this article can be found in the supplementary material.

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Appendix A. Supplementary data

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A.3 Paper II (Bluhm, 2025): Environmental effects of ICT-enabled small-scale energy flexibilities: the perspective of German market players

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Environmental effects of ICT-enabled small-scale energy flexibilities: the perspective of German market players

Hannes Bluhm[1,2*]

[1] Europa-Universität Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany
[2] Institute for Ecological Economy Research (IÖW), Potsdamer Str. 105, 10785 Berlin, Germany

*E-mail: hannes.bluhm@ioew.de

Abstract. Information and Communication Technology (ICT) facilitates the flexibilization of small-scale energy technologies in households. This article investigates the resulting environmental effects from the perspective of German market players. Through qualitative interviews and a semiquantitative survey, the study identifies the perceived positive effects, such as enhanced renewable integration, and the negative effects, including increased ICT infrastructure demands and potential simultaneity effects, which might increase the need for grid infrastructure expansion. Market participants indicate that the perceived benefits outweigh the identified drawbacks, yet they signal the necessity for additional measures to enhance environmental performance and more quantitative impact analyses.

1. Introduction

Small-scale, household-related energy technologies such as battery electric vehicles (BEV) in combination with wallboxes, battery storage systems (BSS), photovoltaic plants (PV), or electric heat pumps (EHP) bear the potential to decarbonize a household's power supply and consumption, as well as heating and mobility needs. In Europe, capacities have expanded rapidly and are expected to increase further towards an energy system based on intermittent renewable energies [1]. In Germany, as the most populous country in the European Union, technologies are about to expand by several multiples compared to their current capacities to achieve a climate-neutral energy system by 2045 (see e.g., [2]).

So far, these technologies have operated without considering external energy system conditions such as wholesale prices, grid stability or the current renewables share in the electricity mix. The introduction of digital Information and Communication Technology (ICT), such as smart meters (SM) and communication gateways, enables a timely measurement of power flows, bidirectional communication between the household and external entities, and an automated external control of household-related energy technologies [3]. As a result, households' power feed-in and -out can be adapted and shifted based on external conditions, thus providing energy flexibility [4]. However, in 2023, only about 1% of households in Germany were equipped with SM systems – compared to up to 100% in other European countries [5].

The roll-out of up to 95% of metering points until 2030 is provided by law [6]. Furthermore, the regulation provides that energy retail suppliers have to offer 'dynamic tariffs' (i.e., contracts

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reflecting price changes at the spot market) as of January 2025 [6], and distribution system operators have to offer variable grid charges (i.e., time windows with different grid charge levels) as of April 2025 [7]. New business models and applications have emerged, such as retailer models offering dynamic tariffs or virtual power plants providing ancillary services [8]. To promote these, companies claim environmental benefits, such as a more sustainable energy supply for the household or the prevention of critical grid conditions for the power system (e.g., [9, 10]).

Research has shown that the environmental effects of ICT in general [11] and in the energy sector in particular [12] can result in both intended and unintended environmental benefits and burdens at various levels. Consequently, the companies' perception of potential environmental effects may be too limited in scope if focused only on potential benefits. On the other hand, due to the increasing large-scale availability of real-life data and increasing practical experience, they may offer valuable insights into effects that researchers have not yet been able to assess sufficiently and give perspective on the relevance of these effects. However, research addressing the business players' perspectives on the environmental effects of ICT-enabled energy flexibilities constitutes a research gap. Therefore, the article addresses the following research questions:

- Which environmental effects of ICT-enabled small-scale flexibilities are market players aware of?
- To what extent are the potential positive and negative effects relevant, and what are the net effects from the market players' perspective?

To address these questions, a two-step research approach includes qualitative interviews with and a semiquantitative survey among German energy companies.

The article contributes to the research gap in two ways. First, by making companies the subject of investigation and involving social science research methods, the article adds another perspective to the discussion of digitalization's environmental effects dominated by environmental and energy science approaches. Second, the transdisciplinary research design uses existing practical knowledge and reflects the empirical results into the scientific discussion on the environmental effects of ICT. In addition, the article aims to outline potential options for improving the environmental performance of ICT-enabled energy flexibilities.

2. Methods

The following subsections describe the environmental effects framework underlying the analysis and two-step approach based on qualitative interviews and a semiquantitative survey.

2.1 Framework of environmental effects of smart energy systems

According to Wohlschlager et al. [12], the environmental effects of smart (or digitalized) energy systems occur at and across three levels. At the technology level, direct effects concerning the life-cycle of ICT are involved, such as the production, operation, and disposal of SM systems. They increase resource and energy demand and result in negative environmental impacts such as more global warming, mineral resource depletion, or eutrophication. Substitutional and optimization effects are called indirect effects at the technology level. Substitution effects occur when a digital counterpart replaces products or services, which can result in both a decrease and an increase in energy and resource demand. Optimization effects arise from process improvement through the use of information (e.g., less CO_2 emissions due to automatized charging of BEVs). Achieving optimization effects is a primary target of numerous digital energy use cases.

The user level refers to effects resulting from behavioral changes driven by the introduction of ICT. Rebound effects result in negative impacts when efficiency gains from ICT lead to financial

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or time savings, increasing overall consumption. Induction effects occur when the availability of more options encourages more intensive usage of ICT-based services. Induction effects also contribute to higher environmental impacts. Positive behavioral changes, such as users actively reducing their energy consumption, are termed beneficial effects.

Effects at the system level refer to changes in the transmission and distribution infrastructures (e.g., lower grid expansion needs due to a more flexible operation of BSSs), as well as in generation and supply (e.g., lower fossil and higher renewable generation due to PV plants), which can result in additional positive and negative impacts.

2.2 Exploratory interviews

To identify potential positive and negative environmental effects of flexible energy technology operations, semi-structured interviews were conducted with middle management representatives of three energy suppliers, one technology provider, and one transmission system operator. The companies and interviewees were chosen based on existing contacts or their involvement in research projects on small-scale energy flexibility.

The interviews were conducted online via MS Teams in November 2023 and lasted about 30 to 45 minutes. The interviews were recorded, transcribed, and analyzed with qualitative content analysis [13]. In two cases, the interviewees sent additional answers via email. Deductive coding was applied based on the taxonomy of environmental effects of smart energy use cases by Wohlschlager et al. [12]. Quotes were assigned to the respective effect level and according to the direction of potential impact (positive, negative, both). The quotes were then paraphrased to summarize and anonymize information.

2.3 Survey

A survey was developed to assess the relevance of the potential environmental effects of small-scale energy flexibility. It consists of two parts: Part I consists of eight screening questions (seven multiple-choice questions and one open-field question), and part II includes eight questions containing 22 assessment items with a five-step Likert scale ranging from “strongly disagree” to “strongly agree” plus “cannot assess”. The latter was included to assess if knowledge of a particular effect is perceived as insufficient for a qualified reply. The questions in part II cover effects at the technology and system levels. Potential effects at the user level were not included to keep the time to reply short and because it is assumed that companies do not have sufficient insights into self-motivated changes in behavior due to flexibilization processes.

In November 2024, email invitations were sent to 160 contacts covering different steps of the value chain of small-scale energy flexibilities. Contacts were identified via existing research projects and a snowball approach on the LinkedIn platform. The focus was on middle management employees in business areas such as product management, regulatory affairs, or business development. Representatives of 18 institutions replied (response rate of 11.3%).

Replies to part I of the survey are presented according to their absolute number of responses. Detailed results are presented in the Appendix. The author has subsequently assigned free-text entries to the specified multiple-choice options in individual cases. Part II of the survey is analyzed based on the relative shares of the response categories in the total number of responses per item. Due to the small sample size (n), further statistical analyses were not conducted.

3. Results

The following subsections present the results of the interviews and the survey.

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3.1 Interviews

General information on the interviewees and the results of the deductive coding approach are presented in Figure 1 and Figure 2.

The interviewees' institutions act as energy suppliers for households with more (C) and less (A, B) than five years of experience in the German market, as well as aggregators (A-D), as original equipment manufacturer (OEM) (D), and as transmission system operator (TSO) (E). A, B, and C address a portfolio of energy technologies with different maturity levels. In contrast, D focuses on EHPs, and E addresses energy technologies only indirectly by developing a communication platform for (inter alia) aggregators and TSOs. Customers are approached differently via dynamic and community tariffs with optional bonuses for external control. The flexibilities are marketed at the energy exchange (spot and forward market) and system service markets.

Regarding direct effects at the technology level (whose life-cycle is per se negative), all interviewees named several ICT components at the household and utility levels necessary to enable small-scale flexibilities. A relevant infrastructure is smart meters and smart meter gateways. A, B, and C use this infrastructure only for official metering and billing. The operation of flexibilities is facilitated via the customers' private internet connection since it enables the necessary data transmission intervals (every couple of seconds) to provide energy services. Customer interaction is organized via smartphone apps and portals. At the utility level, additional own or rented infrastructures and services, such as additional platforms for subcontractor communication, are required. C and E report that blockchain has been tested in pilot projects as a technological option to organize transactions. Still, usage has not been continued since it is not suited, e.g., because required functionalities are more straightforward to realize with other solutions.

As for indirect effects at the technology level, interviewees report that external control can be positive and negative environmental due to optimization. Flexible operation can increase a household's use of renewable energy and decrease its CO_2 emissions. Furthermore, the interaction of PV plants with additional energy technologies in one household can leverage synergies for energy flows and increase the share of PV self-consumption. On the other hand, interviewees report potential negative effects on the BSS' lifetime since flexible operation with feed-in and -out requires additional load cycles. However, this is less of a problem with lithium iron phosphate (LFP) battery systems that provide sufficient load cycles in contrast to other battery types. Furthermore, external control might minimally reduce a household's degree of self-sufficiency. In the case of EHPs, external control might increase the number of compressor cycles, leading to a reduction in the technology's lifetime. In addition, an aggregator's control strategy to overheat the building and shift load can both increase and decrease the household's power consumption depending on the temperatures prevailing at that time.

Three interviewees reported potential effects at the user level: a flexible operation of energy technologies might strengthen the household's sensation of being an active part of the energy transition. This might result in a higher acceptance of the energy transition as a whole.

Effects at the system level cover several aspects and timescales. In the short term, flexible operation supports the leveling of intermittent renewable energy production and consumption. This ensures a stable grid operation, avoids renewable energy curtailment, and substitutes conventional power production. However, a parallel reaction of a larger number of small-scale energy technologies to external signals can cause simultaneity effects that put grid operation under additional pressure, especially if reactions to signals at the transmission system level or market level worsen grid conditions at the distribution system level. However, these effects could

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	Category	[A]	[B]	[C]	[D]	[E]
General information	Role	Energy supplier <5 years in the German market, aggregator	Energy supplier <5 years in the German market, aggregator	Energy supplier >5 years in the German market, aggregator	OEM, aggregator	TSO
	Products	Time-of-use, regional tariff, price-dynamic tariff (in Germany as of 2025)	Price-dynamic tariff	Community tariff, bonus for participation in virtual power plant	Flexible EHP and customer portal	Communication platform for aggregators and TSOs
	Markets	Spot and forward markets; in the future: Redispatch and other system services	Spot market optimization, intraday optimization, in the future: balancing energy market	FCR, spot market optimization	Redispatch, in the future: balancing energy, grid-orientated control in distribution grids (EnWG §14a)	System services: control reserve (primary, secondary, tertiary), congestion management (Redispatch)
	Addressed tech-nologies	EHP (with heat storage), BEV with wallbox (directional charging), BSS, PV plant	BEV with wallbox (directional charging), BSS and inverter control (early phase), EHP (early phase; with and without heat storage), hot water tanks	EHP (with and without storage), BEV with wallbox (directional charging), PV & BSS, in the future: wallbox with bidirectional charging capability, PV plant, air conditioning systems	EHP (with and without heat storage), electric heating element	All small-scale flexibilities
Environmental effects	Technology level (direct)	(-) Household: 1 SM, 1 GW, customer WLAN, usage of virtual EMS, usage of customer app (-) Aggregator & others: Aggregator platform, external server provider, LTE communication via BEV	(-) Household: SM, GW, possibly CLS box, usage of virtual EMS, customer WLAN, and customer app. (-) Aggregator & others: aggregator platform, external server provider, cloud-to-cloud communication (between aggregator cloud to OEM cloud)	(-) Household: 1 SM, 1 GW, customer WLAN or mobile internet, customer portal, customer app, non-calibrated meters, built-in communication technology, and physical EMS in BSS (-) Aggregator & others: redundant servers for FCR (official security requirement), external server provider, partner for energy exchange access, portals for partner communication, blockchain tested but not suitable, 15-30 MB/month via GW (LTE, fixed line, PLC, in the future: 450 MHz)	(-) Household: built-in module or box in EHP, OEM's own digital electricity meter due to lack of access to SM, customer WLAN or possibly LAN, EMS, customer app, in the future: smart thermostat valves with room thermostats (-) Aggregator & others: cloud server for customer data, cloud platform for communication with TSO	(-) Other: bundled data from aggregator to platform with high temporal resolution of few seconds (SM data not suitable), uncalibrated meters (must meet TSO requirements), platform

Figure 1. Interview results (own compilation)

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Environmental effects	Technology level (indirect)	(+) All: Use of renewable energies (-) BSS: Can negatively affect battery lifetime	(+) All: CO2 savings through price-optimized electricity use (-) BSS: Consumption of charging cycles possible, less of a problem with LFP batteries	PV & BSS: Possible minimal negative impact on self-sufficiency (-) BSS: Consumption of charging cycles (therefore conscious, gentle control is required), but sufficient charging cycles are available (±) EHP: Higher and lower electricity consumption possible (shift to times with higher/lower temperatures)	(+) EHP & PV: Self-optimization of energy flows in households with PV system (-) EHP: Higher compressor cycling possible, leading to a shorter lifetime	(-) BSS: impact on lifetime, but problem decreases as battery cycles increase (-) EHP: higher electricity consumption possible due to thermal losses when overheating buildings or shifting to times with lower outdoor temperature
	User level	(+) Sensation of active participation in energy transition (+) Positive contribution to the acceptance of energy transition	/	(+) Sensation of active participation in energy transition	/	(+) Potential additional revenues can positively influence the purchase decision for BSS, BEV, etc.
	System level	(+) Replacing fossil power plants (-) Risk of simultaneity effects with further expansion of technologies and pure price-based control with stress on grid and electricity supply	(+) Enablement of energy system transformation through alignment of volatile generation and consumption (-) Simultaneity effects with impacts on local transformer and grid branch	(+) Integrate renewable energy faster and achieve expansion goals faster (+) Enablement of expansion of assets in households (+) Less curtailment of renewable energy Ensure grid stability (+) More „mindful" use of resources (±) Simultaneity effects and mitigation thereof possible	(+) Reaction of energy technologies to grid signals (+) Alignment of increasingly electrified consumers and volatile renewables (-) Simultaneity effects possible	(+) Replacement of conventional power plants, leaving the market for Redispatch and greater market competition (+) No alternative to grid expansion, but development of grid infrastructure; possibly less local grid expansion (-) Simultaneity effects possible

(+) = Positive environmental impact; (–) = Negative environmental impact; (±) = Both
CLS: Controllable Local Systems, DSO: Distribution System Operator, EMS: Energy Management System,EnWG: Energiewirtschaftsgesetz (Energy Industry Act), FCR: Frequency Containment Reserve, GW: Gateway, LAN: Local Area Network, LFP: Lithium Iron Phosphate, LTE: Long-Term Evolution, OEM: Original equipment manufacturer, PLC: Powerline Communication, SM: Smart Meter, TSO: Transmission System Operator, WLAN: Wireless Local Area Network

Figure 2. Interview results (continued; own compilation)

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also be mitigated by intelligent control. In the long run, flexible operation is what makes the integration of electrified energy technologies and the accelerated expansion of renewable energies possible. This facilitates the necessary system change. Furthermore, opening energy technologies for external signals also contributes to a more “mindful” use of natural resources. Regarding the role of small-scale flexibilities in reducing grid expansion, interviewee E states that flexibilization is not a substitute for grid expansion or is only locally at best.

3.2 Survey

The results of part I of the survey are presented in the Appendix. The results of part II are presented in Figure 3. In the written presentation of results of part II, shares for agreement (“strongly agree”, “somewhat agree”) and disagreement (“strongly disagree”, “somewhat disagree”) are summed up for simplicity.

Part I: Screening questions

Eighteen persons replied to the survey. Except for measuring point operators (no participants), one to four representatives of each contacted group replied. Eight replied that addressing flexibilities is part of the company’s core business, and 10 replied that it is not. The most addressed energy technology are BEVs (11 respondents), followed by EHPs (10), BSSs (8), PV plants (6), white goods (2), and others (2). As for 2030, the number of replies increases for each technology. BEVs remain the most addressed technology (14), followed by BSSs (13), PV plants and EHPs (both 12), white goods (6), and others (1).

The most used or supported tariff models to leverage flexibility are price-dynamic tariffs (9), followed by variable network charges (8), time-of-use tariffs and bonuses (both 5), and community tariffs (3). For comparison: in 2024, about 20 retailers actively offered price-dynamic tariffs in Germany [14]. The flexibilities are used or enabled for different markets, most frequently at the spot market (11), grid management at the low-voltage level (8), Redispatch (7), balancing energy and local market use cases (both 4), the forward market (3), and others (1). The companies facilitate different options to adjust power feed-in and feed-out. The most frequent option among participants is an automatic adjustment according to the customers’ preferences (11 responses), followed by manual adjustments by the customers, and by automatic adjustments according to the optimization strategy of the companies (both 7), as well as others (1).

Part II: Environmental assessment

72% of respondents confirmed that achieving positive environmental effects through the flexible operation of a household’s energy technologies is an important motivation for their company, and none disagreed. Huge flexibility potentials of the technologies were most confirmed for BSS (100%), followed by BEV and HP (both 89%), PV plants (56%), and other technologies (42%, mainly white goods were mentioned).

Regarding direct environmental effects at the technology level, respondents disagree that these are significantly negative at the household level (67%) and the aggregator’s level (73%). However, 94% of the respondents agree that companies must expand their ICT equipment significantly to facilitate their business models.

83% of the respondents agree that flexible operation has positive indirect effects on energy technologies and the household’s energy supply. In contrast, 73% disagree that these effects might be negative. As for effects at the system level, 100% of the respondents agree that these are positive, and conversely, 100% disagree that these are negative.

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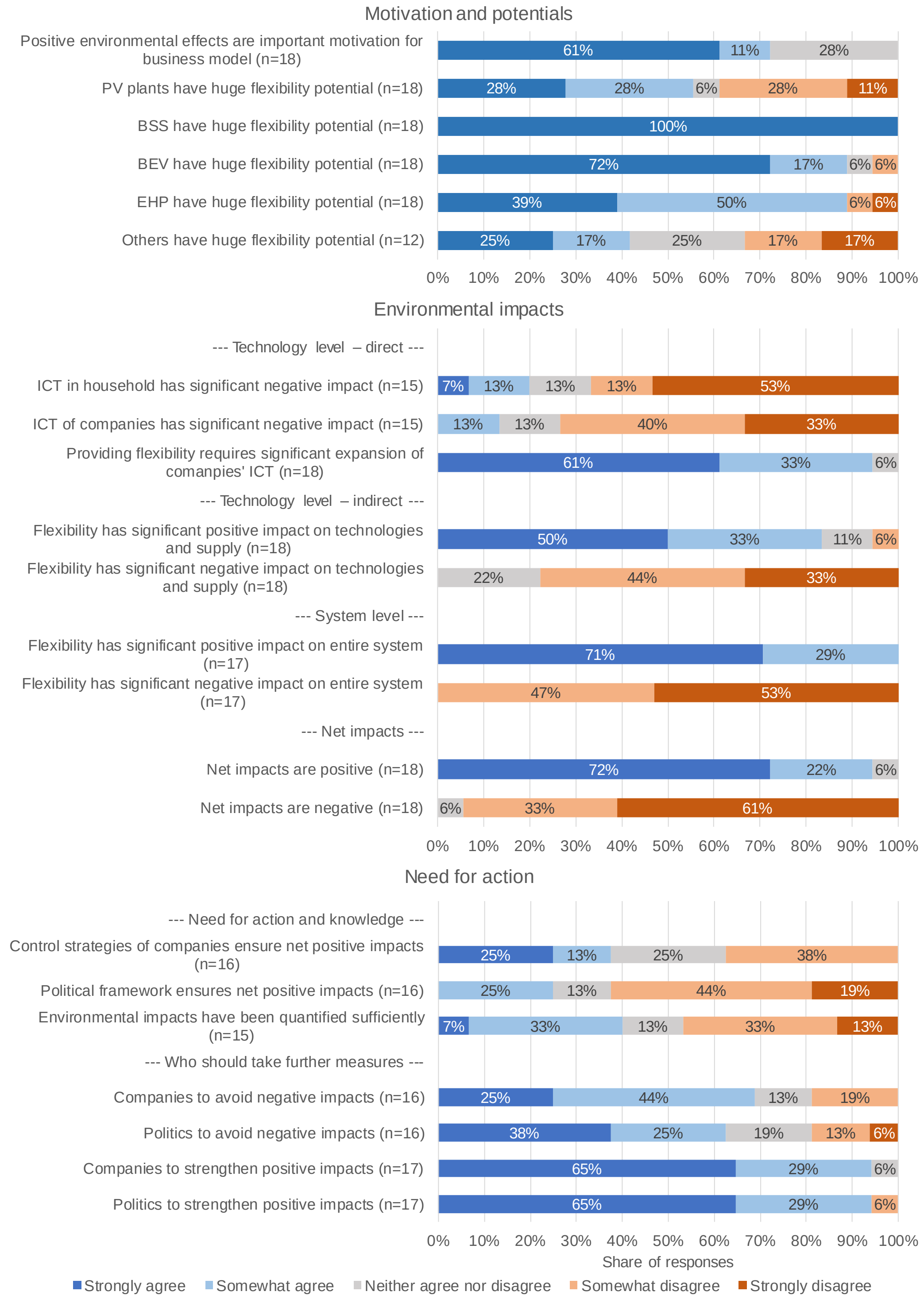

Figure 3. Survey results on environmental assessment (part II)

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Finally, 94% of the respondents agree that net effects across levels are positive, and conversely, 94% disagree that these are negative.

Regarding the need for action, the same percentage of respondents (38%) agrees and disagrees that the companies' control strategies already ensure a positive environmental outcome. With a share of 63%, respondents disagree that the current political framework ensures a positive outcome. That these effects have been sufficiently quantified tends to meet disagreement (47%) rather than agreement (40%). For the items addressing the initiator of further measures to avoid negative impacts, 69% agree that companies should initiate this, and 63% agree that politics should take additional measures. Inversely, 94% agree that companies should take further measures to strengthen positive impacts, and 94% agree that politics should be the initiator.

On average, 1.2 respondents could not assess the relevance of the item. The most common, non-assessable item is the item on other energy technologies with significant potential for flexibilization (6 respondents). None to 3 respondents chose not to assess other items. Thus, a majority of participants considered themselves capable of evaluating the items.

4. Discussion

The discussion is structured along the levels of environmental effects and net effects. For a comprehensible comparison, a focus is set on quantitative LCA studies and global warming potential. The discussion is enriched with possible options to improve environmental performance based on indications from interviews, literature, and current market developments.

4.1 Direct effects at the technology level

Compared to ICT elements considered in quantitative LCA studies on smart energy use cases, the interviewees mentioned several additional items and applications: cloud-to-cloud communication, as well as different portals, virtual energy management systems (EMS), uncalibrated meters, and 450 MHz mobile data transfer. So far, the elements mainly covered smart meters, gateways, as well as LTE, 5G, fixed internet, powerline communication data transfer (e.g., [15–17]), and less often physical EMS [18] and server infrastructures (e.g., [19–21]).

Most survey respondents disagree that direct effects at the technology level cause significant negative environmental impacts. On the other hand, these items related to environmental effects are the most controversial results, as 20% (household's ICT) and 13% (companies' ICT) agree that direct effects can cause negative impacts. Furthermore, since 94% of respondents agree that companies need to increase their ICT capacities significantly to enable flexibilization, one can expect that potential negative consequences due to the production, operation, and disposal of digital components will increase, too.

LCA studies on smart energy use cases state direct effects in a range of 15.7 kg $CO_{2\text{-eq}}$ per year per household for combined PV-BSS systems [19] to 33.4 kg $CO_{2\text{-eq}}$ per year per vehicle for smart charging of BEV [20] and up to 59 kg $CO_{2\text{-eq}}$ per year per household in a worst case scenario for simple smart metering [15]. In unfavorable scenarios, direct effects cannot be overcompensated by indirect effects, which indicates that the life cycle of ICT can be significant in relative terms.

Based on the interviews' indications, three starting points for mitigating direct effects can be derived. First, avoid parallel communication channels via the customers' internet connection, which causes additional data transfer and ICT usage. This could be achieved if upcoming generations of the smart meter infrastructure also fulfilled communication requirements for these markets. Second, virtual EMS might (partially) avoid material and energy consumption for

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physical EMS. Third, companies could strategically aim at enforcing standards and performance indicators for their own and rented server infrastructures.

4.2 Indirect effects at the technology level

The indirect technology effects mentioned by the interviewees address solely the results of optimization processes. These can result in positive and negative effects from the household's perspective. According to the survey results, most respondents agree that the positive effects of flexibilization on the households' energy supply and the lifetime of energy technologies are significant and a majority disagree that the adverse effects are significant.

Several studies state positive environmental impacts due to intelligent control of BEVs and PV-BSS combinations [19, 22–24]. One key effect of price-optimizing charging use cases is that such strategies use the correlation between low electricity prices and high shares of renewable energies. However, this is not always the case, so emissions can also increase [23]. Furthermore, two studies considering changes in the lifetime of battery systems and reduced levels of self-sufficiency show that these effects can potentially void emission savings [19, 25].

Life-cycle effects should be integrated into the aggregators' optimization strategy to avoid adverse effects on the lifetime of energy technologies. Divided survey results on the statement that control strategies already ensure positive impacts indicate that this is also a starting point for improvement. According to two interviewees, this is already the case, if only because poor control strategies can cause a loss of acceptance among customers. Furthermore, using LFP batteries for stationary purposes is seen as less environmentally relevant than using other cell chemistries. Literature shows this is correct concerning robustness and resource depletion [26], however, not for the global warming potential [27]. Thus, market players may be making false assumptions. For improvement, guarantees for a minimum device lifetime by distributors (see e.g., [19]) or thresholds for a minimum lifetime in state support measures could be considered.

Furthermore, the development towards bidirectional charging will accelerate battery degradation of BEVs compared to directional charging [28]. This is also why manufacturers of BEVs already limit load cycles for bidirectional charging (cf. [29]) so that non-driving purposes do not significantly shorten the batteries' lifetime, as one interviewee reported.

Considering environmental effects and not only price effects in optimization strategies is also an option for improvement. According to one interviewee, however, this is a challenge for customer communication because, e.g., longer-term optimization over several days (probably including environmental aspects) can be less intuitive to customers than short-term optimization.

4.3 User level

In the interviews, there were only individual mentions of effects at the user level, which were exclusively positive (increased acceptance towards the energy transition). The impression of the interviewer was that interviewees could not yet base their assessment on experience but instead articulated expectations of user behavior.

This is also why the survey did not include statements on usage effects. However, in part I of the survey, the most common options for setting adjustments for consumption and feed-in are "automatic according to customer preferences" and "manually by customer preferences". Thus, at least while setting these preferences, usage behavior affects environmental performance.

Furthermore, it is assumed that companies cannot fully differentiate between changing energy consumption volumes due to optimization and changes in behavior. In that case, the latter cannot be significant because respondents agree with a majority that the influence on the household's electricity is positive, and they disagree that the impact is negative.

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Empirical results for variable tariff options [30] and research on smart metering [21], PV prosumage [31], and smart homes [32] show that usage effects can be both significantly positive (sufficiency) and negative (rebound and induction). This suggests that market players need to be more aware of the relevance of usage effects and the need to outweigh potential rebounds through their control strategies.

Market players can provide relevant information and set suitable default configurations to support customer decisions and improve environmental performance. For example, the German retailer Green Planet Energy offers a dynamic tariff with additional signals to customers for times with low and high renewable energy shares [33].

4.4 System level

Interviewees are aware of several potential effects leading to positive environmental impacts and negative impacts. Compared to Wohlschlager et al.'s taxonomy [12], the effects articulated by interviewees appear more nuanced as they can be differentiated according location (grid, demand-side, supply-side, and matching of demand and supply), scales of time (short-term and long-term effects, acceleration of change), and the intended environmental impact (changes in energy or resource volumes).

All survey respondents agree that the positive effects of flexibilization on the energy system are significant, and they disagree that the adverse effects are significant. On the other hand, the divided survey results on the statement that companies' control strategies already ensure positive impacts could indicate that respondents perceive a need for action to prevent negative effects at the system level.

The effect of flexible energy technologies triggering changes in the power plant dispatch and capacities is highly relevant and primarily positive in LCA studies for PV-BSS combinations [19] and BEVs [23, 34, 35]. This is mainly because they increase the use of renewable energies and substitute the need for larger-scale flexibility measures. The effect on low-voltage grid infrastructures is researched by Wohlschlager et al. [22]. Compared to direct, uncontrolled charging of BEVs, they find that bidirectional charging causes additional grid reinforcement needs (lines and transformers) and line losses.

To avoid adverse effects, potential measures concerning the control strategy of aggregators as described in section 5.2 also apply at the system level, or they might be a compromise between interests of the household (e.g., less flexibility usage due to loss of comfort), the aggregator (more flexibility usage for offering system services), and system operators (more or specific flexibility usage). Furthermore, the introduction of variable grid tariffs in Germany as of April 2025 is intended to mitigate critical grid situations [7].

Removing barriers to the large-scale introduction of flexibility is key to enabling the positive effects at the system level to unfold. According to interviewees, politics must accelerate the roll-out of smart meter infrastructure and make it cheaper for households. A novel coalition of market players in Germany suggests several measures to expedite the roll-out process, e.g., by co-use of existing communication infrastructures for heat meters [36]. Furthermore, interviewees suggest abolishing any double-charging of price components for stored and discharged energy, harmonizing standards across the several hundred German distribution system operators, and integrating small-scale flexibilities in the amendment of the Redispatch organization (so-called “Redispatch 2.0” [37]). As for the company side of enabling large-scale integration, one interviewee suggested a “technology agnostic” approach, meaning that aggregators should be open to any energy technology and any manufacturer and model.

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4.5 Net effects

According to the survey results, the respondents agree that environmental effects from flexibilization are net positive, and they disagree that net effects are negative. Thus, market players pursue their business model while expecting an environmentally beneficial outcome for the flexibilization of household-related energy technologies – despite per se and potentially occurring negative effects. This is in line with the majority agreement that achieving a positive environmental outcome is an essential motivation for the companies' business models. It again seems contradictory that the respondents do not unambiguously assume that the companies' management strategies ensure net positive effects and that the majority of them see a need for action by politics and companies to improve environmental impacts.

From existing LCA literature, three studies make statements on net environmental effects and across levels of effects [19, 22, 23]. They find that net effects are achievable, but this depends on the operational strategies and markets served, as well as on the environmental effects considered. In unfavorable constellations, these effects can lead to net negative impacts.

Against this background, the companies' environmental effects assessment appears overly optimistic. Thus, market players' awareness of the existence and relevance of effects should be raised, and measures in the players' sphere of influence should be considered. Furthermore, the availability of studies somehow contradicts the survey respondents' assessment that effects have not yet been sufficiently quantified. Thus, there might be a problem with the availability of knowledge but also with the transfer of knowledge. However, potential adverse effects in worst-case scenarios should not be a reason for delaying the needed flexibilization but an indication of how to avoid net burdens.

Measured against the survey results, BSSs, followed by BEVs and EHPs, have the most significant potential for flexibilization [38] and should, therefore, be the focus of services that market players offer in the market launch phase. In doing so, they should consider that their framing of consequences of flexibilization can influence the customers' willingness to provide flexibility. Furthermore, households with PV-BSS combinations and BEVs are more willing to provide flexibility than those with EHPs [38].

4.6 Limitations

The results and discussion must be considered against the background of several limitations. First, the interviews and the survey are based on comparably small sample sizes (n). In the case of interviews, this limits the qualitative capturing of environmental effects from different groups of business players. As for the survey, the low population hinders the application of statistical significance tests and the analysis of correlations between variables.

Second, the intention of keeping the survey short led to aggregated questions that hindered a differentiated analysis of responses (e.g., environmental effects and need for measures by technology). Thus, in these cases, only general statements can be made.

Third, the survey responses might contain a motivational bias, meaning that participants tend to respond based on beliefs and expectations rather than objective observations [39].

4.7 Future research

Interview and survey results indicate that scientific knowledge of environmental effects might be insufficient for a comprehensive assessment. Therefore, further quantitative analysis, e.g., LCAs considering effects and their impacts across levels of effects, can support decision-making. With the increasing diffusion of flexibilization in the years to come, effects can be analyzed and validated based on individual case studies and large-scale real-life data. In doing so,

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inter- and transdisciplinary approaches can help capture various environmental effects, e.g., by integrating methods from environmental psychology or energy system analysis.

Individual aspects of further research that occurred during interviews are differences between physical and virtual EMS and the quantification of potentially reduced grid expansion needs due to flexibility.

The existing research gap on stakeholder perspectives on environmental effects indicates that analyzing additional perspectives could help to check whether there are specific, shared, or contradicting goals, expectations, and knowledge regarding environmental effects across stakeholders. Analyzing further stakeholder groups and potential measures to address environmental effects could help ease, harmonize, and prioritize goals and measures.

5. Conclusion

This article assesses the environmental effects of ICT-enabled small-scale energy flexibilities from the perspective of German market players. Using qualitative interviews and a survey, it explores the potentially occurring environmental effects and captures their relevance at technology, user, and system levels. While companies highlight the potential environmental benefits, such as enhanced renewable energy integration and optimized energy use, they are also aware of potential burdens due to increased ICT infrastructure needs, reduced battery lifetime, or potential challenges for electricity grids.

The findings indicate that market participants expect net environmental impacts to be positive. However, there are areas for improvement concerning mitigating additional burdens and strengthening benefits. By implementing a sensitive control strategy, aggregators assume a pivotal role in achieving environmental outcomes at various levels and fostering the acceptance of energy flexibility use cases. Compared to existing LCA studies, the market players' assessment of net effects appears justified but too optimistic concerning the occurrence of negative effects. From a political standpoint, the facilitation of the smart meter roll-out and the enforcement of services based on it, such as the obligatory offer of dynamic tariffs and variable grid charges, can pave the way for positive environmental outcomes on a broad scale. Finally, addressing both positive and negative effects is crucial to achieving a climate-neutral energy system by 2045 and an environmentally sustainable one beyond greenhouse gas emissions.

Future research should focus on differences in expectations regarding environmental effects and impacts across stakeholders and cooperation with market players to evaluate large-scale real-world data that will become available through market diffusion. Ultimately, this work highlights the need to transfer knowledge on environmental effects from science to practice.

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Data

The survey results and the interview guide are provided in a Zenodo repository, see [40].

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Appendix

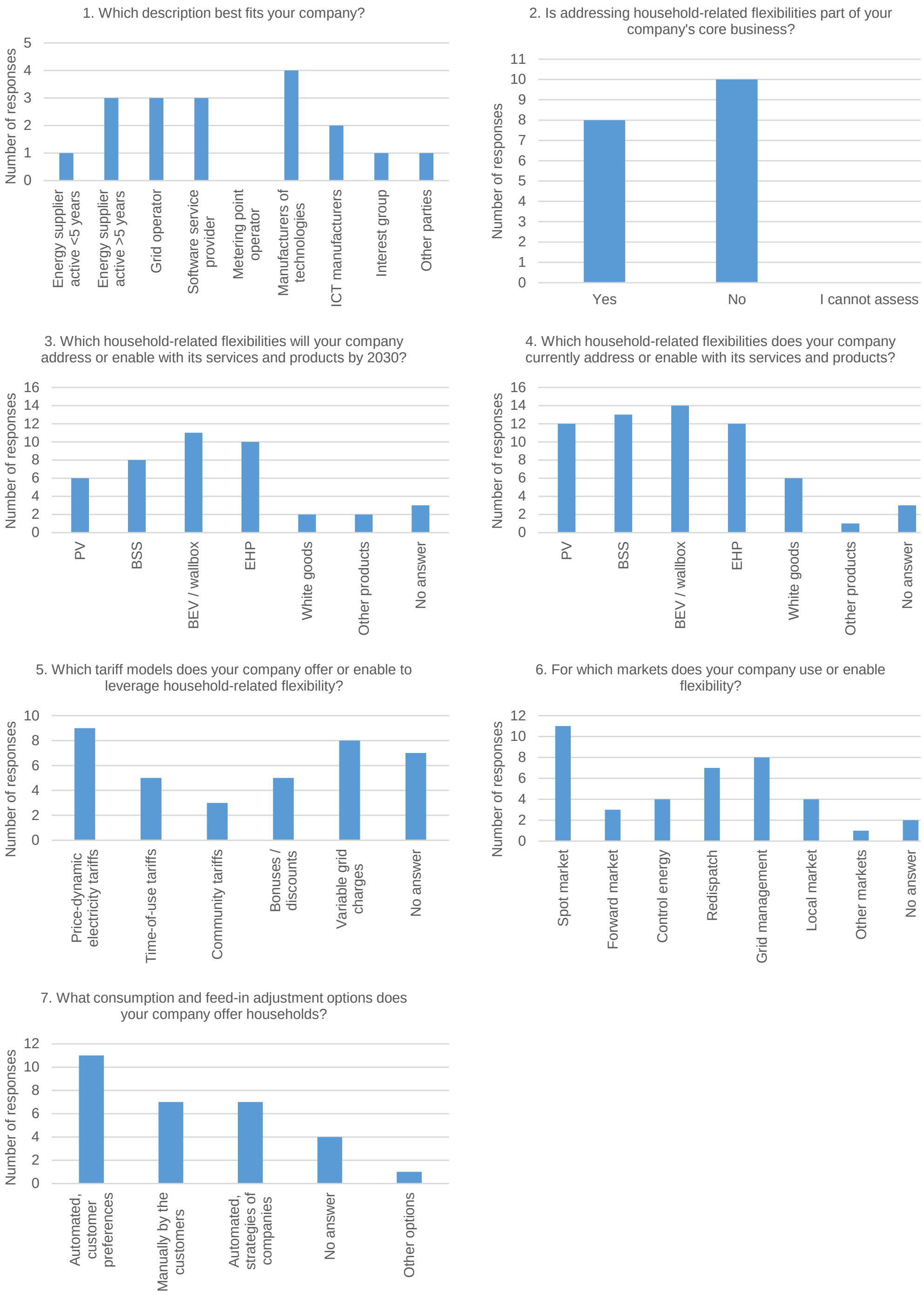

Figure 4. Results of part I (screening questions) of the survey

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Research Papers

Environmental assessment of prosumer digitalization: The case of virtual pooling of PV battery storage systems

Hannes Bluhm [a,b,*], Swantje Gährs [a]

[a] Institute for Ecological Economy Research, Potsdamer Straße 105, 10785 Berlin, Germany
[b] Europa-Universität Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany

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ABSTRACT

The emergence of decentralized renewable energies together with digitalization enable new possibilities for the provision of system services that are needed for the energy transition. In Germany and worldwide, prosumers with a PV battery storage system are on the rise. With the aid of digital information and communication technologies (ICT), energy service providers can pool individual battery storage units to form a virtual battery energy storage system (VBES). The VBES is supposed to provide flexibility services and, thereby, support the transition towards an energy system with high shares of intermittent renewables. Although the concept is environmentally motivated, a holistic environmental assessment is missing so far. Therefore, we carry out a life-cycle analysis that considers environmental benefits, as well as burdens of VBES. For this, we compare a PV battery storage unit in a German single-family household with and without participation in a VBES for the year 2018. We assess three levels of environmental effects: direct effects due to digitalization (data transfer, ICT resources for VBES operation), indirect effects from external optimization on the household-level (changes in battery life and power supply), and enablement effects on the system level (provision of Frequency Containment Reserve, redispatch, and preventing renewables curtailment). We find that digitalization has a comparably low direct impact but it can enable relatively high environmental benefits for climate protection, and in other impact categories. Conditions for our findings are that battery life and the household's degree of self-sufficiency with PV electricity are not significantly affected by the external control of the VBES operator. We conclude that current and future battery owners should be encouraged to allow external access for system services. Furthermore, the necessary ICT roll out should be implemented in the short- to mid-term.

1. Introduction

In Germany and worldwide, the installation and use of small-scale battery storage systems in combination with roof-top photovoltaic power plants (PV battery storage systems) are about to expand significantly. According to German Transmission System Operators, battery storage units with a rated power of 77 to 98 GW and a capacity of 153 to 196 GWh must be installed by 2045 to achieve a climate-neutral power system [1]. By comparison, those installed in 2021 had only 2 GW and about 4 GWh [2].

At a global level, IRENA [3] forecasts installed small-scale PV batteries with capacities of between 56 and 236 GWh by 2030. IEA [4] predicts that by 2050, zero emission targets will require an installed power of 3100 GW and a capacity of 12400 GWh for both small-scale and large-scale batteries. Of these targeted figures, only 18 GW were installed in 2020.

The production and disposal of PV battery systems is resource-intensive [5] – a factor that energy planning and scenarios have scarcely addressed thus far. One way to broaden the use of these technologies and thereby increase resource efficiency is to implement virtual battery energy storage (VBES). In VBES, digital information and communication technologies (ICT) facilitate an external monitoring and management of distributed energy resources like privately owned PV battery storage systems [6,7]. Such a setup enables providers to aggregate local, regional or national battery energy storage pools – either in isolation or together with other technologies – in virtual power plants (VPP). The pooling allows them to provide flexibility and system services, which in turn supports the transition towards a decarbonized energy system characterized by a high proportion of intermitting renewable energies. First commercial providers are already pursuing the

* Corresponding author at: Institute for Ecological Economy Research, Potsdamer Straße 105, 10785 Berlin, Germany.
E-mail address: hannes.bluhm@ioew.de (H. Bluhm).

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concept in Germany and other countries [8].

Since the PV battery storage concept itself is meant to support the shift into a sustainable energy system, it makes sense to see promoting climate protection and other environmental targets as a key motive for pooling the systems. Thus far, however, there has been no holistic environmental assessment of the concept which considers both the burdens of additional ICT infrastructure and the benefits of its enablement effects. This study will address this research gap by investigating the following research questions:

- What are the environmental burdens and benefits of PV battery pooling in light of ICT infrastructures, and how do they compare to the life cycle impacts of energy technologies?
- Which energy system services can provide net environmental benefits?

The aim is to give a more holistic environmental assessment of the burdens, benefits, and potential effects of PV battery pooling, focusing on the impact of providing energy system services. With respect to burdens, we consider digital infrastructures and technological backlashes through external battery management. On the benefit side, we analyze the provision of selected energy system services. For the sake of comparison, we also compare impacts on the life cycle of the PV battery system. For this, we carry out a Life Cycle Analysis (LCA) based on international guidelines.

The structure of the article is as follows: Section 2 outlines the technical and organizational concept of PV battery pooling and reviews scholarship on the environmental effects of digital technology. Section 3 discusses the LCA methodological approach. Results are presented in Section 4, followed by a discussion in Section 5. Our conclusions are presented in Section 6.

2. Background

2.1. Virtual pooling of PV battery storage systems

One way private households can participate in the energy transition is by becoming prosumers – that is, by generating and directly consuming their own energy. Among electricity generating technologies, photovoltaic systems are the most popular because solar systems can be installed on most roofs. As small batteries become more and more common among prosumers, it makes sense to use them not only for self-consumption, but also to support the energy system as a whole. This is especially true given that the batteries in private households go partially unused in winter and summer. That untapped power can help balance energy or stabilize the grid in the overall system [9]. While the capacity and market-balancing performance of individual batteries is too small, it can be profitable when aggregated through a controlled pool [10]. The latter could consist of batteries alone (what is sometimes called a virtual battery energy storage system or VBES), or take the form of a virtual power plant made up of batteries and other technologies. In this article, we focus on the VBES format. A VBES operator will have external control over the batteries in a specific pool, and can also use weather data, forecasting, and knowledge of the markets for ancillary services to optimize battery management. Two real life examples are the PV battery storage pooling for several thousand PV batteries that Germany's Sonnen and Lichtblick companies are currently doing to provide Frequency Containment Reserves (FCR) and other energy system services [11–13]. Other companies, like Next Kraftwerke, use a similar concept by pooling large-scale batteries in a virtual power plant (Next [14]) or by cooperating with aggregators of small-scale batteries such as Sonnen [13]. Additionally, some research projects are investigating whether and how PV battery energy storage units can contribute to the overarching energy system (e.g. [10,15–17]).

To set up a VBES by pooling decentralized PV battery storage units, one needs a suitable ICT infrastructure. This includes the technology found in private households as well as that housed with the VBES operator and the DSO or utility company (cf. Fig. 1). There is not one fixed ICT set-up for a VBES; however, there are some general requirements that will be accounted for in this article. At the household level, some kind of metering system is needed to monitor the status of the PV system and the battery and control the battery. As smart meters are mandatory in Germany for PV systems over 7 kWp ([19], § 29 (1)), we assume – as an ideal-typical example – that there are two digital meters and one smart meter gateway as a communication gateway. When smaller PV systems or older PV battery storage systems are retrofitted for external management, analogue meters will likely have to be replaced by digital systems. Private households usually connect to the Internet through their home area network or a neighborhood network, so no extra infrastructure is needed [18]. In order to store and process the data and send it to the service operator (e.g. DSO, utility company or trading platform), the VBES operator will also need to own or rent a server at a data center [18,20] and will need an ICT infrastructure as the control center for the services is located there.

One main goal of pooling batteries is to use them for other services. In general, batteries are suitable for various ancillary and system services, as Kumar et al. [16] analyzed for several countries. Of these potential uses, the following are relevant for Germany: (1) voltage control, (2) scheduling/dispatch, (3) frequency control, (4) energy balancing, (5) supplemental reserve, (6) black start, (7) demand turn-up & inter-trip, (8) transmission must run and (9) system restoration. In their categorization of ancillary services, Maeyart et al. [10] also found six services that are interesting for decentralized prosumers, since they can generate an economic benefit. These are three services to increase the grid quality (Voltage Regulation, Frequency Regulation and Congestion Relief) and three service for cost saving (Demand Response, Self-consumption and Energy Arbitrage). In general, these are also relevant services for VBES. This article will only focus on selected services that can improve grid quality, namely Frequency Containment Reserves (FCR) for frequency regulation, redispatch, and prevention of the curtailment of renewables to avoid grid congestion. Voltage regulation will not be addressed, as there is no market for this in Germany. Although we here discuss the services separately, all services are needed, especially in a future 100 % renewable energy scenario. Some of them can also be combined, as they have very different specifications regarding battery usage; however, this would make the environmental analysis much harder. Therefore, we focus on one service at a time and discuss the results together.

The market for balancing energy is highly regulated and it is controlled by the TSOs. FCR is a service TSOs use to maintain a frequency of 50 Hz within the power system, with limited variations [21]. FCR provision is only permitted for systems of 1 MW and higher, so PV battery storage systems can only access it via a pool. As a condition of FCR provision via batteries, German TSOs require that full power be provided for a certain length of time. In 2018, this minimum time was set to 30 min, with a required ratio of capacity to rated power of at least 2 kWh/kW [22]. However, this standard was found to be disproportional and invalid by the German Federal Network Agency. Therefore, in 2019 it was revised to 15 min, which doubled the marketable battery power [23]. However, pending the results of a TSO cost-benefit analysis that has yet to be submitted, this regulated value might rise to between 15 and 30 min [24]. In addition, the IT infrastructure requirements set by TSOs to ensure availability, confidentiality, integrity, reliability and authenticity [25] can only be met by a professional aggregator – not by every single prosumer household. German TSOs contracted a volume of 620 MW in 2018 and 573 MW in 2020 [26]; thus, VBES have only limited possibilities in this market.

If dispatching schedules of conventional generators threatens to cause overload of power grid elements, TSOs can guarantee system stability by instructing power plants to reduce or increase feed-in, either under contractual agreement or legal obligations. In 2018, feed-in of 5436 GWh was reduced for these reasons, while feed-in of 5418 GWh was increased elsewhere. Redispatch interventions were also mandated

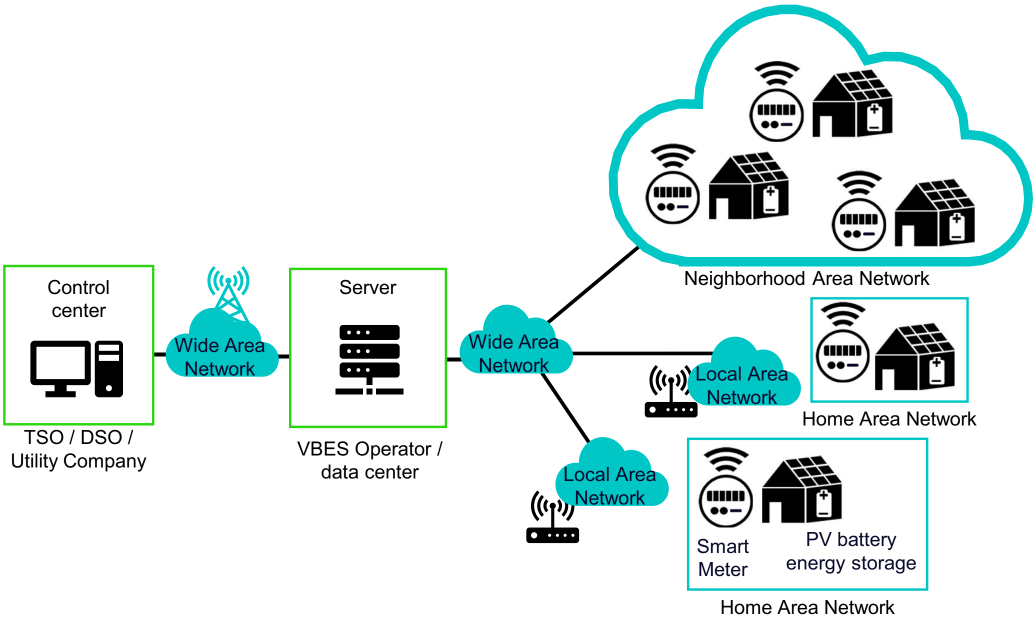

Fig. 1. Digital infrastructure for virtual pooling of battery energy storage, based on Zajc et al. [18].

in 6865 h of the year. TSOs can also curtail renewable feed-in when necessary.

The energetic and financial waste of these interventions is not insignificant. Thus, 5403 GWh of mostly wind but also solar energy could not be consumed in 2018 [21]. The figures for both redispatch (total of 16795 GWh) and curtailment (6146 GWh) increased until 2020 leading to costs of 1.4 billion euros [26]. As grid expansion options fade and renewable generation increases, we can expect the need for and costs of system services to increase in the future.

Since October 1, 2021, the redispatch and the curtailment of RES have been combined into one service, dubbed 'Redispatch 2.0'. The service was introduced via the Grid Expansion Acceleration Act (NABEG 2.0) of 2019. Before that, RES had played a special role and were not part of the redispatch; rather, DSOs and TSOs were allowed to cut off the RES when necessary. Redispatch 2.0 includes all electricity generators with an installed capacity over 100 kW. This means that the curtailment of RES is planned in advance, and that operators can use battery storage to prevent this. The combination of the two services might change the market. Because this change is quite new and there is no available data for Redispatch 2.0, we will assess the services separately. In 2018, redispatch was necessary for 5418 GWh and the curtailment of RES came close, with 5403 GWh.

2.2. Environmental effects of digitalization in the energy sector

One way to pursue a more holistic environmental assessment of PV battery pooling is to examine how the digital devices required for pooling trigger different environmental effects. These environmental effects of digitalization can be seen through the filter of certain perspectives ([91,92]; [27]):

- The **technology perspective** addresses the direct environmental effects of the material and energy consumption required to produce, use and dispose of digital applications like smart meters and sever units. It also covers the indirect environmental effects of substituting analogue applications and the often-intended optimization through monitoring and improved control mechanisms;
- The **user perspective** takes into account the environmental effects (like rebound and induction effects) of users' consumption behaviors, both additional environmental loads like rebound and induction effects, as well as beneficial impacts like sufficiency and spillover effects;
- The **system perspective** considers the potential of applications to impact across economic sectors due and thus, for example, to stimulate growth or effect lifestyle changes if they achieve greater market diffusion. In the energy sector, this may cause overall electricity demand to change, affect the resulting needs for generation capacity and electricity grid expansion, and cause changes in the electricity mix.

Considering this categorization, we could not find holistic environmental assessments for the concept of PV battery pooling but rather analyses addressing individual effects of similar business models.

Regarding PV prosuming, Schram et al. [28] focus on the greenhouse gas reduction potential that can be achieved through PV installations and battery usage for individual households and households in a local energy sharing community. Rossi et al. [29] perform an LCA for PV home systems with battery storage in eight European countries. Moshövel et al. [30] carry out an LCA for a PV prosumer household with different types of batteries and for two different charging strategies. The studies do not consider environmental burdens from digital devices; they mainly cover the technology perspective.

In terms of direct effects, smart meters and smart meter gateways are a technological prerequisite for PV battery pooling. Wohlschlager et al. [31] analyze the environmental footprint of smart meters, focusing on impacts from device production and operation; however, they do not consider data transfer and enablement effects quantitatively. Sias [32] analyzes the direct and enablement effects of smart meters, but does not address impacts from data transfer. Gährs et al. [27] use secondary data on the production phase of smart meters, and consider the effects caused by data transfer, as well as enablement effects from a user and system perspective in five energy related use cases. More focused LCAs and meta analyses of internet data transfer can be found in Andrae and Edler [33], Bordage et al. [34] and Coroama [35], for example. In this regard, only a few studies consider both energy and resource consumption of data transfer and depict the entire data transfer process.

With regard to the system effects of technological approaches similar to PV battery pooling, we could identify LCA studies by Immendoerfer et al. [36] and Stenzel et al. [37]. Both analyze the environmental impact of providing FCR via large-scale batteries versus hydro pump storage plants and hard coal plants. They reach different conclusions regarding the environmental benefits and burdens of the FCR approach, but in so doing neglect to assess the direct environmental impact brought on by the required digital infrastructures.

Beyond LCAs, numerous studies focus on techno-economic assessments of small-scale and large-scale batteries providing system services (e.g., [38–42]), on overall systemic effects of private batteries being managed externally (mainly system costs, electricity mix, grid and generation expansion, grid conditions and carbon dioxide emissions, e.g., [43–47]) or on VPPs with other energy technologies being addressed (e.g., [48–50]; [51,52]).

With our focus on a more holistic LCA across the perspectives of potential environmental impacts and different system services and by focusing on pooling of small-scale PV battery storage units, we intend to address a research gap in scientific literature.

3. Methods

3.1. Life cycle assessment

Life cycle assessment is a standardized method for "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [53]. The method can help different stakeholders demonstrate the environmental impact of products along their life cycle phases and identify opportunities for improvement. Products in this context include services, software, hardware, and procedural technical products, which can be tangible or intangible [53]. Due to its goal and its and broad product definition, we follow Gährs et al. [27] and find LCA a suitable method for environmentally assessing ICT devices and the services they provide in energy-related contexts like PV battery pooling.

According to international guidelines, a LCA study should cover four phases [53]:

- Definition of goal and scope,
- Inventory analysis,
- impact assessment,
- interpretation.

For our case study, we address the definition of goal and scope and the inventory analysis in the following subsections. Impact assessment and interpretation are presented in Sections 4 and 5.

3.2. Goal and scope

The goal of the LCA is to comparatively analyze the environmental benefits and burdens of PV battery storage units which are integrated in a virtual battery energy storage (hereinafter "VBES case") versus those without external management ("Ref case"). This is of interest because PV battery system installation and use is expected to increase significantly in the future.

Our target groups are actors from politics, industry, and academia whose work is focused on the use and the environmental impact of digital applications in the energy sector and who deal with the strategic role of energy communities in the energy transition.

Our analysis looks at the concept from the technology and system perspectives. For the sake of simplicity, the user perspective is not addressed in our study; rather, we assume that battery pooling has no unique impacting factors. For the sake of comparison, we also assess the life cycle of the PV and the battery system.

The system boundaries of the Ref and VBES case cover material and energy flows for the production, use and disposal of both ICT goods (for a household and the pooling operator) and different energy system services. For the sake of comparison, we also assess the environmental burdens of household energy supply (see Fig. 2). The functional unit is the power supply of a single-family prosumer household with an electricity demand of 4000 kWh for one calendar year. The demand can be categorized in accordance with the Stromspiegel, a regular survey of German consumers [54]. According to this document, our four-person household is located in the middle of the observable consumption range [55].

The supply includes the electricity grid supply, the PV electricity self-consumption, and the PV electricity feed-in into the public electricity grid. Locally, the case study refers to a household in Germany with an average PV electricity yield. We assume that the respective legal, technical and energy-economic framework conditions for our reference year, 2018, apply here. Guidelines for the provision of certain system services have been revised since then, and might change again (see Section 2.1).

We use attributional LCA (ALCA) as system modelling approach. The approach uses historical, verified and measurable data [56]. To account for the environmental benefits from system services provision, we use system expansion; that is, we treat those services as by-products that substitute the average market mixes for each.

Guidelines for LCAs of ICT only require that we assess climate change and energy consumption as impact categories [57,58]. We regard the focus on these two categories as insufficient when considering multidimensional, planetary boundaries. Thus, we expand our impact assessment to include the categories suggested by Schödwell and Zarnekow [59], as well as additional categories of the impact assessment method provided by the Dutch Centrum voor Milieukunde of the University of Leiden [60] and the cumulative energy demand (lower heating value) by Weidema et al. [61]:

- Global warming potential (GWP) in kilogram of carbon dioxide equivalents (kgCO2eq),
- Abiotic resource depletion potential (ADP) in kilogram of antimony equivalents (kgSbeq),
- Cumulative energy demand (CED) in megajoule of primary energy (MJ),
- Acidification potential (AP) in kilogram of sulphur dioxide equivalents (kgSO2eq),
- Eutrophication potential (EP) in kilogram of phosphate equivalents (kgPO4eq),
- Ozone layer depletion (ODP) in kilogram of chlorofluorocarbon-11 (kgCFC-11eq),
- Photochemical ozone creation potential (POCP) in kilogram of ethene (kgC2H4eq).

The aim of the inventory phase was to depict a common reference case, as well as market-typical components and processes. All information was derived from publicly available sources, or energy industry companies that are active in battery pooling, or else the author's own assumptions (which are identified as such). All unit process data for the inventory items stems from the Ecoinvent 3.5 [62] and ÖKOBAUDAT [63] databases, or are based on the datasets modelled by Gährs et al. [27]. As LCA modelling software, we use SimaPro 9.0.

Since the available primary data on PV battery pooling is limited and since we mainly rely on generic data and estimations, our study has the characteristics of a screening LCA [56]. Therefore, the results presented here should not be considered as definitive, but rather as a first assessment of the technological principle and its environmental potential.

The authors of this case study are familiar with the LCA method, the scope of PV prosuming and digitalization in the energy sector. Our interest is scientific.

This case study was conducted as part of two publicly funded research projects (see Acknowledgements) pursuing a transdisciplinary approach. This has enabled us to take into account the knowledge and

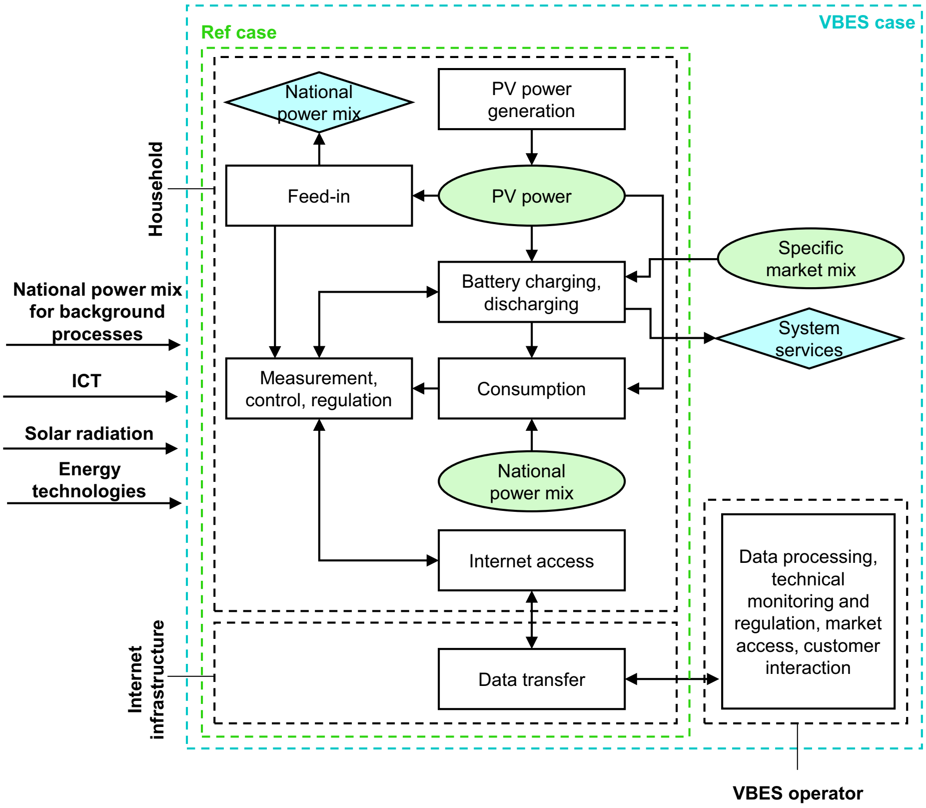

Fig. 2. System boundaries for the Ref and VBES cases.

perspectives of different stakeholders from politics, science and business.

3.3. *Life-cycle inventories*

The life cycle inventory starts with the basic equipment used both in the reference and VBES cases. The remaining inventories are structured according to the perspectives presented in Section 2.2 to account for the different environmental impacts of digital appliances.

A tabular overview of the LCA inventory can be found in the Appendix.

3.3.1. *Energy technologies*

Identical technological systems are assumed for both the Ref and VBES cases. Drawing on our interview with a VBES operator, the PV output for the case study was set at 9 kWp. The interview partner justified the assumed output by the regulatory advantages of systems up to 10 kWp ([64], § 61a) in Germany. VBES customers tend to buy systems slightly below that limit. In comparison, the average rated power of PV systems in 2017 was 8.1 kWp [65]. For the LCA modelling of the plant, we used a generic ÖKOBAUDAT dataset that included a mix of PV technologies typical for the German market. The dataset accounts for the material and energy expenditures for panels, cabling, mountings and inverters [66].

The storage system is a lithium iron phosphate (LFP) battery with a capacity of 9 kWh. This type of battery is sold and used for battery pooling, for example by the German companies Sonnen [67] and Lichtblick [11]. LFP batteries are known for their lack of reliance on the critical resources cobalt and nickel, and for being more robust and durable than nickel-manganese-cobalt (NMC) batteries. The rated power (3 kW) is based on the 2017 average for installed small-scale batteries [68]. The resulting ratio of usable battery capacity to nominal PV system power of 1.0 kWh/kWp corresponds to the German market average for 2017 [65]. For the LCA modelling, we used an ÖKOBAUDAT dataset that reflects the environmental impact per kWh of storage capacity. The efficiency of the battery is given as 92 %. The dataset also takes into account the energy and material input for control and regulation electronics [69].

Based on the PV and battery system configurations, we estimate household self-sufficiency to be 79 % (that is, 79 % of consumed energy is supplied by the household itself, and 21 % by the German public electricity mix). We also estimate that 38 % of the PV electricity produced is consumed by the household itself, with the remaining 62 % of PV electricity production being fed into the grid, where it substitutes part of the public electricity mix. These values are based on normalized analyses by Weniger et al. [70] who simulated various combinations of PV battery storage systems with measured load profiles for 74 households across Germany.

Instead of installing a PV battery system, the household could procure electricity solely from the grid (“pure grid supply”). This additional case is depicted for the sake of comparison.

3.3.2. *Direct effects*

In our case study, direct effects from digitalization refer to the ICT infrastructures that are needed by the household and by the VBES operator, as well as the data traffic and processing in the background. Certain ICT items are presumably installed and used from the outset (Ref case). Others have to be assigned solely to the VBES case.

We assume that the household needs two digital meters and one gateway for each case (Ref and VBES): one for recording PV feed-in, one for recording storage feed-in, with a gateway connected to the internet via the Home Area Network (HAN). Although a reference case without an installed smart meter is beyond the focus of our analysis, we briefly discuss the potential impact of this scenario in Section 4.

Based on interview responses, we assume that 1 GB/a of data is transferred in the Ref case. In the VBES case, 1 GB/a of additional data traffic is sent to the VBES operator, and an additional 0.2 GB/a comes from customer portal usage. This value is based on our assumption that residents in the household spend a total of 100 min/a on the portal. We combine the figure with industry target values for visit length per webpage and typical data consumption rates per webpage [71,72]. To manage the storage pool, the operator uses three independent rack servers, each equipped with 18 height units. A three-shift operation with three employees per shift, all of whom use laptop computers, is also assumed. These assumptions are based on our interview responses. Drawing on the market share of the largest German home storage provider, Sonnen, we estimate the number of participating households in the pool to be 32000. There is no information available for the volume of data traffic from other processes, such as control signals or market participation (e.g. communication between the operator and TSOs). We assume that the volumes are negligible when allocated to one household. Furthermore, we analyze the effect of higher data traffic in a sensitivity analysis (see Section 4.4). Inventory data for ICT devices and data transfer are taken from Gährs et al. [27].

3.3.3. Indirect effects (technology perspective)

To assess the indirect effects from a technology perspective, we consider those effects on the structure of the household's electricity supply and the battery life.

3.3.3.1. Changes in power supply. For the VBES case, it is assumed that pooling aims to maximize PV electricity usage among all participating households for consumption in the pool and other services. Studies simulating charging behavior in such a pool could not be identified. However, from personal communications with industry players and from Loock et al. [73], we know that operators use weather forecasts in their energy management.

Various studies have investigated the difference between battery control strategies that aim to optimize self-consumption versus those that seek to optimize grid consumption or are forecast-based. They found that these two latter alternative control strategies have no [44] or only a minor influence [30,74,75] on levels of self-sufficiency vis-à-vis strategies to optimize self-consumption. During the course of a given year, in other words, the shares supplied by the grid and by PV power hardly differ between control strategies. By contrast, changes occur at shorter time intervals, e.g., during the course of a single day.

Based on the literature reviewed, we make the simplified assumption that external battery management has no influence on the modelled household's level of self-consumption. However, we investigate the potential influence of this management strategy in our sensitivity analysis.

3.3.3.2. Changes in battery life. Beyond the effect on self-consumption, different studies find that forecast-based charging strategies and external management have only minor effects on the operating characteristics of the battery storage – that is, on the number of full cycles and the average state of charge (cf. [44]). Moshövel et al. [30] even report that such strategies have a positive effect on the lifetime of lithium-ion batteries. The presumably low impact is also supported by the fact that VBES operators guarantee a sufficient number of load cycles and – in the case of external control with LFP batteries – even report a positive influence [67,76].

We therefore neglect the effect of changes in battery in our starting analysis but estimate the potential impact of both shortening and extension in our sensitivity analysis.

3.3.4. Indirect effects (system perspective)

We compare four systemic services of storage pooling to our reference case. For each service, we assume that the VBES operator substitutes a representative kilowatt hour or kilowatt of a certain market mix. We also assume that the pooling operator only provides one service per point in time. This allows us to investigate the ideal-typical environmental effect per service.

For providing system services, the VBES operator accesses only a fraction of the battery's capacity and rated power. The real-life operator Lichtblick [76] states that it uses about 10 % of the capacity for system services. Furthermore, 15 to 20 full load cycles per year are needed to provide FCR in 2021. We use these values as a starting point for assessing the battery's potential to provide different system services.

3.3.4.1. Frequency containment reserves. Based on the stipulations of 2018 and our assumed storage device, we derive a battery power marketable for FCR of 0.45 kW (or 15 % of the battery's power) that can be provided throughout the year. The figure can be reproduced applying the following formula:

$$\frac{\text{Share of capacity for VPP operation*Battery capacity}}{\text{Battery power marketable for FCR}} = \text{Required capacity power ratio} \overset{!}{=} 2\frac{\text{kWh}}{\text{kW}}$$

In order to determine the environmental burden of FCR via PV batteries, we assume 8.75 full load cycles,[1] resulting in a consumption of the national market mix of 175.0 kWh per kW of FCR and year, or 78.8 kWh for 0.45 kW*a.

The environmental burden of the historic FCR mix is determined per kW and year. The substituted electricity mix is based on the structure of prequalified FCR power [77] and on a personal communication with a German TSO, according to which bids for battery capacities are typically successful in tenders. Thus, about 37 % of FCR was provided by battery storages, a further 37 % by hydroelectric plants like pump storage units, 19 % by fossil-fueled plants, and 6 % by nuclear plants (see Appendix).

3.3.4.2. Redispatch and preventing the curtailment of renewables in the grid. Storage capacity could be also used for services like redispatch and the prevention of renewables curtailment in the grid. For the market potential, the 17.5 full load cycles per year imply a charging of 157.5 kWh and a discharging of 144.9 kWh considering our assumed battery characteristics.

In case of redispatch, the battery is loaded with the average national electricity mix and it substitutes the average redispatch mix for feed-in. In 2018, the latter was mainly provided by natural gas plants (38 %), hard coal plants (37 %), foreign power plants (15 %), and hydro pump storages (8 %) [21].

For preventing renewables curtailment, the battery is loaded with the average mix of curtailed renewables (97 % wind and 2 % PV, [21]). The stored energy then substitutes the national electricity mix (Table 1).

4. Results

4.1. Energy technologies

The environmental effects of the household energy supply are presented by comparing the case of pure grid supply (= 100 %) and the case of PV prosuming with battery storage in the Ref case. For the prosumer household, the environmental impacts of the energy supply are both lower and higher than pure gird supply. GWP, AP, EP, ODP and CED yield values from −18.9 % to −107.0 %, meaning that feed-in – and,

[1] 17.5 full load cycles for 0.9 kW/a of FCR in 2021 converted to 8.75 full load cycles for 0.45 kW/a in 2018.

Table 1
Substitution ratios for system services per year.

	FCR	Redispatch (power increase)	Preventing renewables curtailment in the grid
Charged electricity mix	78.8 kWh of general national mix	157.5 kWh of general national mix	157.5 kWh of national mix of curtailed renewables
Substituted electricity mix	0.45 kW of FCR mix	144.9 kWh of redispatch mix for power increase	144.9 kWh of general national mix

thus, substitution – from the national electricity mix overcompensates for the impacts of battery- and PV-plant production, as well as grid supply. On the other hand, POCP is only partially compensated for (85.4 % of pure grid supply) and ADPE is higher (+93.7 %) than it is in the case of pure grid supply. This is due to PV plant production and disposal, in the first instance, followed by battery production and disposal (Fig. 3).

4.2. Direct effects

We compare the direct environmental impacts of digitalization by comparing the case of prosuming (Ref = 100 %) against the case of PV battery pooling (VBES) (see Fig. 4).

For both cases, direct effects from the production, use and disposal of digital appliances represent environmental burdens in all impact categories; in the VBES case, however, these burdens are 2.4 % to 15.7 % higher than in the Ref case, with GWP and CED showing the highest increases. This is because additional data volumes were sent and received by the household and infrastructure of the VBES operator. In all impact categories, additional burdens come mainly from the VBES infrastructure. Here, over 93 % of environmental impacts come from the production, operation and disposal of rack servers.

If we were to assume a Ref case that features analogue rather than digital installed meters, we would have to assign to the VBES case not only the additional burdens, but also all direct effects. This first estimation, however, neglects the environmental effects that could arise from the premature decommissioning of the analogue meters.

Compared to the production and disposal of PV plant and battery storage units, additional direct effects account for 3.9 % of the EP impacts and less than 0.3 % of the impacts associated with other categories.

4.3. Indirect effects

The environmental impacts of system services provision are presented as multiples of additional direct effects in Fig. 5. Values above 1 indicate net additional burdens. Values between 0 and 1 mean a reduction but yet, not full compensation of direct effects. Values below the zero line indicate that direct effects can be overcompensated.

In the majority of services and impact categories, indirect effects of digitalization result in net environmental benefits. FCR can trigger the highest environmental reliefs. GWP is −656.2 kgCO2eq or − 340 times the direct effects. Values for AP, EP, ODP, POCP and CED are between multiples of −166 and − 275. ADPE, however, leads to additional net burdens of 32 %. Impacts of FCR double if we do not assume FCR stipulations for batteries of 2018 but current ones (not depicted in Fig. 5). Preventing curtailment in the grid is entirely beneficial. The GWP is −64.3 kgCO2eq or − 32 times the direct effects. With multiples of −0.4 to −30, other impact categories show likewise the potential for overcompensation. Results for Redispatch go in different directions. Benefits are indicated for GWP (multiple of −6), ODP (−25), and POCP (−3). However, net environmental burdens are prevalent for AP (2), CED (6), and EP (27).

In the case of digital meters replacing analogue ones, we see that the environmental relief would still be significant for FCR and the prevention of renewables curtailment with multiples of up to −41, except for ADPE, which is about to 1.0 for both services. Redispatch shows mixed results, with multiples of −1 to 3.

4.4. Sensitivity analysis

To address uncertainties in our assumptions, we carry out a sensitivity analysis. For this, we vary several parameters related to the direct and indirect effects of digitalization. A starting point for our analysis is the absolute GWP (1.9 kgCO2eq) and ADPE (4.9E-5 kgSBeq) difference between the Ref and the VBES case with respect to direct effects (Fig. 6).

At the household level, we vary the data transfer volumes for accessing the client portal and those sent to the VBES by ±50 %. At the VBES operator level, data transfer volumes and equipment are varied by ±100 %. From a technology perspective, we vary the battery's lifetime by ±0.7 years (or ± 3.5 %) in order to account for potential positive and negative effects that can arise from externally managing the battery storage unit. The bandwidth is based on the number of load cycles for system services, as reported by Lichtblick [76] (here: 17.5 load cycles per year amount to 350 cycles over 20 years) and the total number of

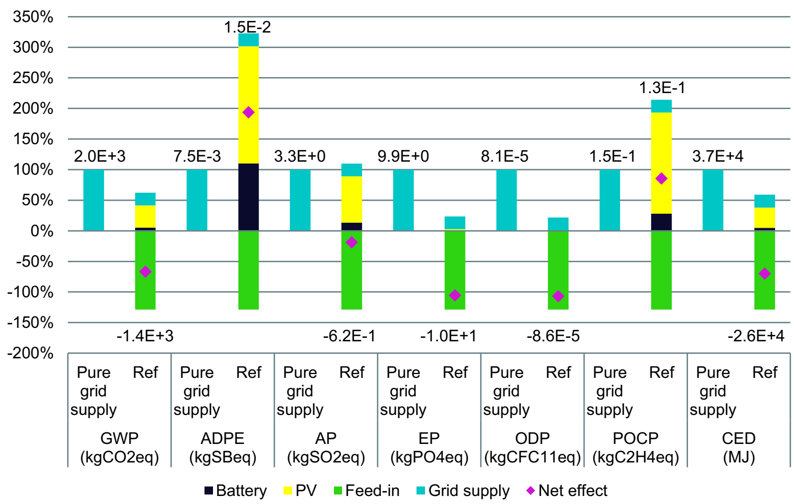

Fig. 3. Impact assessment of energy technologies in the Ref case versus that of pure grid supply (absolute figures appear above the columns).

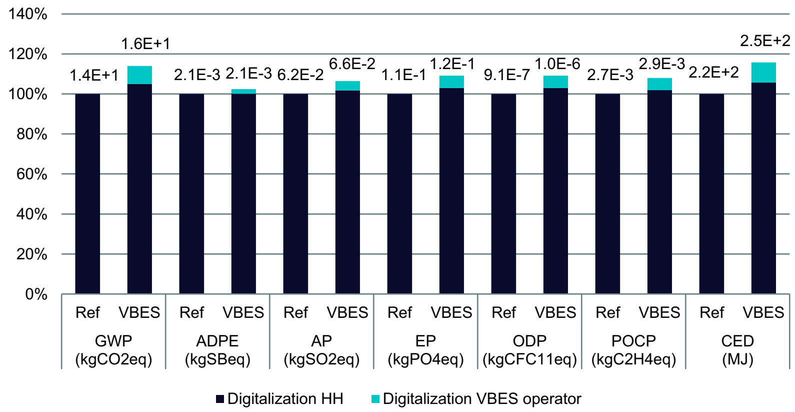

Fig. 4. Impact assessment of digital infrastructure in the Ref and VBES case (absolute figures above columns).

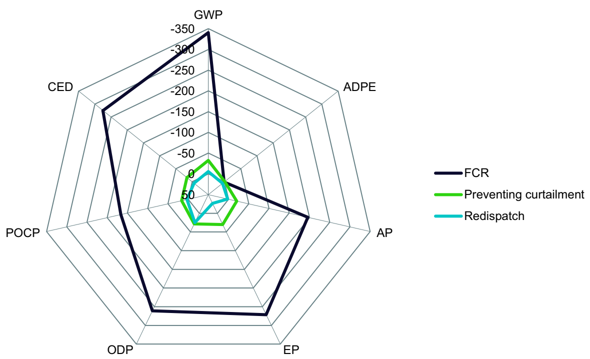

Fig. 5. Impact assessment of system services as net multiples of additional direct effects (inverted axis).

load cycles (10000 cycles) guaranteed over the battery's lifetime by producers like Sonnen [67]. We also analyze a reduction in the household's degree of self-sufficiency, since the strategies chosen by the operator may have such an effect. Lichtblick [76] confirms that the degree of self-sufficiency is "minimally affected" when prosumer households participate in its virtual battery pool. Accordingly, we vary the degree of self-sufficiency by −2.7 percentage points (or − 3.5 %) and increase the share of grid supply. This figure is based on simulations of private and community battery storage units for energy services by Wiesenthal and Schnabel [78].

As measured against the slope of the curves, these results show that variations in data transfer at the household level and in VBES operator infrastructures have a rather low impact on the GWP (±32 % for both parameters) and ADPE (up to ±48 %) differences. Results are more sensitive to changes in battery life (GWP: +194 %, −81 %; ADPE: +610 %, −468 %) and changes in self-sufficiency (GWP: +29 times higher; ADPE: +419 %).

FCR and the prevention of renewables curtailment could compensate for additional GWP impacts; however, GWP benefits from redispatch cannot fully compensate for losses in self-sufficiency. Additional ADPE impacts from impairment of battery life and self-sufficiency cannot be compensated for, since ADPE is already a net burden or only marginally beneficial in the VBES base case.

5. Discussion

For our case study of PV battery storage units as part of a VBES, we identify the environmental burdens and reliefs from several perspectives.

Our LCA results for the required energy technologies show that PV prosuming with batteries alone is environmentally beneficial in comparison to pure grid supply (with the former offering up to 207 % fewer impacts), except for ADPE (up to 94 % additional impacts). PV prosuming is thus a valuable option for private households, as it can reduce the environmental footprint of their electricity supply and support the

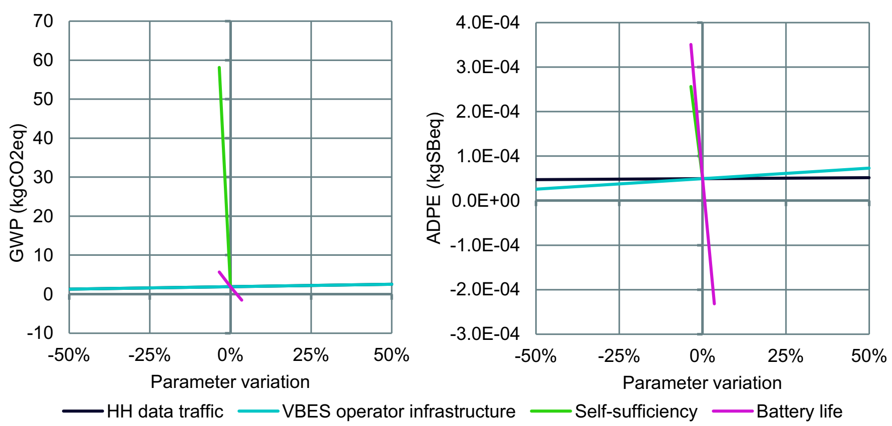

Fig. 6. Sensitivity analysis for GWP (left) and ADPE (right).

energy transition. Nevertheless, for additional benefits and a more efficient use of abiotic resources, we should also consider energy system services provision via external battery management. Results can change if the location, the type of equipment, and the relations between rated power of the PV plant, battery capacity and electricity consumption are altered. Although we assumed an average PV yield, it should be noted that a low variance of the degree of self-sufficiency and own consumption is only present if a higher or lower irradiation is assumed [70]. Furthermore, the LCA datasets used depict representative products that are available at the market. The footprint of the energy equipment could be further reduced by extending lifetimes beyond 20 years. This is already a common assumption in LCA studies with respect to PV technologies [79], and is also suggested by battery producers [67]. Furthermore, resource-efficient product design and recycling processes remain bound by the need to reduce ADPE impacts, in particular. A more detailed discussion of the differences between and backgrounds of energy technologies is beyond the scope of this paper.

Direct effects of digitalization in the VBES case represent additional environmental burdens of up to 15.7 % in relation to the Ref case. The infrastructure needs of the VBES operator are more relevant to the footprint than the additional data volumes sent to and from the household. However, direct effects only account for a small proportion of the effects, in comparison to those resulting from the energy technologies.

In the future, direct effects can be expected to fall due efficiency gains in data processing, storing and transferring, a more renewable energy mix supplying ICT infrastructures, as well as improved ICT production and recycling. On the other hand, our case study approach only assesses incremental changes in direct effects by looking at individual households. If digital concepts like PV battery pooling broadscale in the future, individual effects might sum up to systemic relevant impacts.

Sensitivity analysis of direct and indirect effect from technology perspective shows that results are quite robust in the face of changes in digital requirements. On the other hand, a relatively small change in battery life can significantly affect results. However, VBES operators and research affirm that providing system services might not negatively affect lifetime, and may even enhance it. Furthermore, even a minimal reduction in self-sufficiency can significantly impair environmental benefits – but only if these PV electricity volumes are actually curtailed and not fed into the grid. Thus, VBES operators should weigh any loss in PV power generation against the resulting environmental effects, in addition to the economic ones.

Indirect effects from system perspective are likely to provide environmental benefits. With few exceptions, the benefits yielded by provision of energy system services can compensate (and even overcompensate) for additional direct effects of digitalization. When expressing net benefits and burdens as multiples of environmental differences, results increase in robustness as the multiples increase in number. FCR yields the highest reliefs in most impact categories, followed by preventing curtailment in the grid, followed by redispatch. As compared to direct effects, reliefs can add up to several multiples; redispatch, on the other hand, can yield net environmental burdens in four impact categories (ADPE, AP, EP, CED). For GWP, as the central impact category for climate policies, benefits appear to be robust across services. In our use case, therefore, digitalization is not a critical source for additional environmental impacts; rather, it enables the realization of environmental benefits if system services are provided. We suggest, therefore, that current and future owners of PV battery systems should be encouraged to allow access to and external management of their storage units by VBES operators.

Our estimations on the technical potential of certain system services are, we believe, conservative. First, this is because FCR guidelines for battery storages were eased in Germany in 2019, which effectively doubled the power that can be offered per capacity. Second, our assumed battery power of 3 kW only reflects the average value for batteries installed in 2017. Between then and 2021, however, this figure has grown to 4.5 kW [2], and is expected to grow further [80]. Thus, the power that can be offered for FCR services is higher than we assumed. Thus, we suggest that the current FCR stipulation be maintained and that more restrictive ones not be imposed. Third, the percentage of the battery's capacity used for system service could be increased beyond 10 %. Wiesenthal and Schnabel [78] show that up to 17 % of capacity is available for secondary use on a weekly basis without compromising self-consumption, and could be increased up to 45 % on a daily basis. However, there are also reasons to believe that market potentials may be lower than indicated. In general, the placing of capacities at the markets might not be as successful as we assumed. During operation, the operator must consider the battery's technical restrictions, such as the current state of charge.

The potential environmental benefits per unit of system service can also be optimized: reliefs will increase if VBES operators procure energy mixes in hours with renewables shares above yearly market averages and/or discharge in hours with renewable shares below market averages. However, this dispatching strategy might conflict with the operator's commercial optimization strategy. For this reason, political and industry actors should continue to develop the technical and economic framework conditions to support an environmentally efficient, external use of flexibility options such as PV battery storage units. In the mid- to long-term, furthermore, the environmental benefits of system services are likely to decline as more renewables enter the markets and fossil-based plants exit them, to the point where mere renewable mixes eventually substitute other renewable mixes. That would foreseeably lead to the increasing alignment of charged and substituted electricity mixes in terms of their characteristics and would make their environmental effects less pronounced. As part of this development, other environmental impact categories (such as land use and water consumption), and social impacts that differ for different kinds of clean energy technologies, might gain importance.

Finally, our results should be interpreted in view of our choice to conduct a screening LCA, which means that we identified key processes and based our life cycle inventory on estimated data. In addition, lack of data prevented us from evaluating certain background processes due to a lack of data.

Our attributional LCA approach neglects economic market conditions and dynamics as well as future perspectives. Comparing results to real-life operational data from energy suppliers could further clarify the real degree of success achieved by PV battery pools. Applying consequential approaches by coupling LCA and energy system analysis could also help illuminate how batteries interact with the market environment for current and future energy systems. This could yield significantly different results than those found using attributional LCAs [81,82].

As for the market mixes that are being substituted, for the purposes of this study we assumed that the environmental burdens can be allocated solely to each of the involved services. Because generators within the mix may supply different markets simultaneously, however, impact allocation (for example, through economic allocation) may be a methodological alternative.

Future investigations could also extend the research focus to include other effects from a user and system perspective. At the level of single-family households, we do not expect battery pooling itself to trigger user-related impacts. These might become relevant, however, if VBES operators were to provide certain economic incentives or tariff structures, such as lump sum payments for residual grid supply, that can trigger rebound effects. Furthermore, PV prosuming alone (independent from pooling) can trigger higher electricity consumption due to psychological mechanisms. On the other hand, preliminary research data and feedback from industry actors suggest that PV prosuming and pooling can lead to more energy-sufficient consumption, providing an impetus towards more sustainability in other areas of consumption (i.e. spill-over effects) [27,83]. Finally, user-related impacts themselves can add up to systemically relevant magnitudes [84].

At the system level, grid expansion from low- to high-voltage levels offers a potential future research focus. Studies show that PV battery storage units can provide grid relief and reduce expansion needs (e.g., [9,75]). Environmental assessments for battery pooling are still missing.

Beyond exploring certain effects, research could be extended to include similar flexibility concepts triggered by digitalization, such as pooling of electrical heat pumps, electric vehicles, or community energy storage systems. The latter also present an alternative to the installation of individual storage devices, and already show signs of significantly reducing capacity needs and costs per household [38,85]. The concepts might also be compared to more distant flexibility measures, such as Power-to-Gas.

6. Conclusion

Via digital infrastructures linking several thousands of prosumer households and service operators, virtual battery energy storage (VBES) systems can provide energy system services within a pool. To assess the environmental relevance of this concept, we carried out a life cycle assessment (LCA) and compared how a PV battery storage unit in a German single-family household performed with and without participation in a virtual battery energy storage pool. Our study assumed the legal, technical and energy-economic framework conditions that were valid for 2018. Our LCA results under the assumed conditions suggest that this concept offers several potential environmental benefits – especially regarding climate protection (GWP), in view of the environmental burdens from ICT equipment. Yet these findings also indicate that VBES may trigger new burdens, depending on the service provided and on the impact category. In this regard, redispatch delivers mixed results, whereas preventing the curtailment of renewables, and especially providing Frequency Containment Reserves (FCR), may deliver predominantly environmental reliefs. Among impact categories and across services, VBES is most likely to create additional burdens for mineral resource depletion (ADPE).

Based on our results, we consider digitalization in the energy sector for use cases like VBES concepts to be more of an environmental opportunity, especially in the area of climate protection, than a risk. Therefore, we strongly recommend that the regulatory and technological framework for rolling out the required ICT infrastructures in the energy sector in the short- to mid-term be implemented. Furthermore, we suggest that current and future owners of PV battery units should be encouraged to allow external access to and management of for their systems. By doing this, energy technologies that are expected to be expanded anyway can provide the flexibility needed to implement energy transition processes. In this way, the concept can help to spread resource depletion and other environmental impacts from the PV battery life cycle across a broader set of services. To exploit the potential of VBES in Germany, we make further recommendations in the associated publication of Gährs et al. [27].

Our results also suggest that maintaining the current FCR stipulations is environmentally more beneficial than the more restrictive ones that could potentially result from ongoing cost-benefit analysis by German TSOs, and that environmental reliefs from system services provisions can also be optimized. In light of these findings, we urge political and industry actors to address the technical and economic framework conditions of VBES operations to ensure an environmentally efficient dispatching of decentral flexibility options such as PV battery storage units.

CRediT authorship contribution statement

Hannes Bluhm: Conceptualization, Investigation, Methodology, Formal analysis, Software, Data curation, Writing – original draft. **Swantje Gährs:** Methodology, Investigation, Validation, Writing – original draft, Visualization, Project administration, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

A.1. Life cycle inventory

The following table contains the life cycle inventory for the Ref and the VBESS case. All information were derived from publicly available sources, are based on personal communications with actors from industry, or they are based on own assumptions which are identified as such.

Table 2
Life cycle inventory for case study on VBES.

Case and effect	Item	Size	Unit	Life-time in years	Source for type and size	Source for LCA modelling
Basic equipment	PV plant incl. Cabling, fasteners and inverters	9	kWp	20	Personal communication	BMWSB [66]
	LFP battery incl. Control, and regulation electronics	9 / 3	kWh / kW	20	Personal communication	BMWSB [69]
	Electricity feed-in (substituting national supply mix)	8315.8	kWh/a	–	Based on Weniger et al. [86]	See Table 7
	Grid supply (procuring national supply mix)	840.0	kWh/a	–	Based on Weniger et al. [86]	See Table 7

(continued on next page)

Table 2 (*continued*)

Case and effect	Item	Size	Unit	Life-time in years	Source for type and size	Source for LCA modelling
Reference case						
Direct effects	Smart meter	2	p	12	Personal communication	Gährs et al. [27], Ecoinvent 3.5
	Smart meter Gateway	1	p	12	Personal communication	Gährs et al. [27], Ecoinvent 3.5
	Electricity consumption of smart meters and gateway at 2 W each, 8760 h/a (electricity consumption additional to household consumption; 21 % of the electricity is provided by PV battery system)	52.6	kWh/a	–	Gährs et al. [27]	See Table 7
	Data transfer	1	GB/a	–	Personal communication by VBES operator	Gährs et al. [27], Ecoinvent 3.5
VBES case						
Additional direct effects (household)	Data transfer to VPP operator	1	GB/a	–	Personal communication	Gährs et al. [27], Ecoinvent 3.5
	Data transfer client portal	0.2	GB/a	–	Own assumption	Gährs et al. [27], Ecoinvent 3.5
Direct effects (VBES operator)	Rackserver	3*18	Height units	3	Personal communication, own assumption	Gährs et al. [27], Ecoinvent 3.5
	Electricity consumption at 140 W, 8600 h/a	65016.0	kWh/a	–	Gährs et al. [27]	See Table 7
	Laptops	9	p	3	Personal communication, own assumption	Gährs et al. [27], Ecoinvent 3.5
	Electricity consumption at 19 W, 8760 h/a	499.3	kWh/a	–	Gährs et al. [27]	See Table 7
	Number of clients being provided by ICT system	32000	Clients	–	Based on Sonnen [88]	–
Indirect effects (technology perspective)	Changes in battery life	±0.7	a/20a	–	Based on Lichtblick [76]	[69]
	Changes in self-sufficiency (replaced by national supply mix)	−3.5	%/a	–	Based on Wiesenthal and Schnabel [78]	See Table 7
Indirect effects (system perspective)	Own consumption for FCR	175.0	kWh/ kW*a	–	Based on Lichtblick [76]	See Table 7
	Available power for FCR	0.45	kW/a	–	Based on German TSOs [22]	See Table 3
	Market potential for redispatch and preventing curtailment in the grid	144.9	kWh/a	–	Based on Lichtblick [76]	See Table 5 and Table 6

A.2. Electricity mixes for system services

The following tables show the share of technologies per electricity mix.

A.2.1. Frequency Containment Reserves (FCR)

The calculation is based on a personal communication with a German TSO according to which there is no statistics on the share of generator types providing FCR due to pooling privileges. However, according to the German TSO, battery storages typically win FCR auctions since it is their primary business model.

Table 3
Parameters for FCR.

Technology	Prequalified power	Share w battery	Share w/o battery	Auctioned power	Share w battery	Own consumption for FCR
Source	German TSOs [77]	Own calculation	Own calculation	Own calculation	Own calculation	Based on Stenzel et al. [89]
Unit	GW	–	–	GW	–	kWh/kW
Nuclear	0.50	9.1 %	9.5 %	0.04	6.0 %	8760
Lignite	0.67	12.2 %	12.7 %	0.05	8.1 %	8760
Hard coal	0.69	12.6 %	13.1 %	0.05	8.3 %	8760
Natural gas	0.23	4.2 %	4.4 %	0.02	2.8 %	8760
Biogas, Biomass	0.02	0.4 %	0.4 %	0.00	0.2 %	8760
Water[a]	3.08	56.1 %	58.6 %	0.23	37.1 %	121.4
Battery storages	0.23	4.2 %	–	0.23[b]	36.7 %	121.4
Demand side mgmt	0.07	1.3 %	1.3 %	0.01	0.8 %	–
Sum	5.49	100.0 %	100.0 %	0.62	100.0 %	–

[a] Own assumption: pump storage.
[b] Own assumption based on personal communication with German TSO.

Table 4
Auxiliary calculation for FCR.

Parameter	Value	Unit	Source
Sum w/o battery	5.26	GW	Own calculation
Auctioned FCR	0.62	GW	BNetzA and BKartA [21]
Availability battery	99	%	Danish Energy Agency [90]
Auctioned FCR w/o battery	0.39	GW	Own calculation

A.2.2. Renewables curtailment in the grid

Table 5
Parameters for renewable curtailment in the electricity grid.

Technology	Electricity	Share
Source	BNetzA and BKartA [21]	Own calculation
Unit	GWh	–
Wind (onshore)	3890.5	72.0 %
Wind (offshore)	1356.3	25.1 %
Solar	116.5	2.2 %
Biomass incl. Biogas	35.7	0.7 %
Other	3.6	0.1 %
Sum	5402.6	100.0 %

A.2.3. Redispatch (increased generation)

Table 6
Parameters for redispatch.

Technology	Electricity	Share
Source	BNetzA and BKartA [21]	Own calculation
Unit	GWh	–
Lignite	3	0.0 %
Natural gas	2374	37.9 %
Nuclear	3	0.0 %
Oil	76	1.2 %
Pump storage	521	8.3 %
Reservoir	2	0.0 %
Hard coal	2312	36.9 %
Unknown (exchange trading)[a]	968	15.5 %
Sum	6259	100.0 %

[a] Own assumption: national electricity mix.

A.2.4. Public, national electricity mix

Table 7
Parameters for national electricity mix in Germany.

Technology	Electricity	Share
Source	Based on Fraunhofer ISE [87]	Own calculation
Unit	TWh	–
Wind offshore	19	3.5 %
Wind onshore	89	16.4 %
Biomass	42	7.8 %
Renewable Waste	5	0.9 %
Photovoltaics	40	7.4 %
Run-off river	17	3.1 %
Hard coal	72	13.4 %
Lignite	135	24.9 %
Nuclear	72	13.3 %
Natural gas	45	8.2 %
Oil	1	0.1 %
Non-renewable waste	6	1.0 %
Sum	542	100.0 %

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A.5 Paper IV (Ouanes et al., 2022): Prosuming – energy sufficiency and rebound effects: Climate impact of changing household consumption patterns in Germany

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RESEARCH ARTICLE

Prosuming – energy sufficiency and rebound effects: Climate impact of changing household consumption patterns in Germany

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Nesrine Ouanes*,[1], Jan Kegel[1], Jan Wiesenthal[1,2], Clara Lenk[1], Hannes Bluhm[1,3], Julika Weiß[1], Lukas Torliene[1]

Abstract • Changes in energy consumption patterns after becoming a prosumer household are rarely associated with negative environmental effects, as prosuming is intuitively assumed to be emission-reducing. This paper demonstrates the importance of sufficiency-oriented energy prosumer behavior for climate neutrality goals by quantifying GHG emissions for photovoltaic (PV) prosumers at the German household and energy system level. Based on the results, recommendations are derived for promoting energy sufficiency in prosumer households.

Prosumer – zwischen Energiesuffizienz und Rebound-Effekten: *Klimawirkungen sich verändernder Haushaltsverbrauchmuster in Deutschland*

Zusammenfassung • *Änderungen im Energieverbrauchsverhalten durch den Wechsel zum Prosuming werden selten mit negativen Umwelteffekten in Verbindung gebracht, da intuitiv angenommen wird, dass Prosuming immer emissionsmindernd ist. Ziel dieses Beitrags ist es, die Bedeutung des Suffizienzverhaltens von Energie-Prosumern für die Klimaneutralitätsziele nachzuweisen und die Treibhausgasemissionen auf Haushalts- und Energieystemebene in Deutschland zu quantifizieren. Basierend auf den Ergebnissen werden Empfehlungen zur Förderung der Energiesuffizienz in Prosumer-Haushalten abgeleitet.*

* *Corresponding author: nesrine.ouanes@ioew.de*
[1] *Institute for Ecological Economy Research, Berlin, DE*
[2] *Leuphana University Lüneburg, Lüneburg, DE*
[3] *Europa-Universität Flensburg, Flensburg, DE*

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Introduction

To decarbonize the energy system and achieve climate protection goals, significant increases in renewable energy production are needed. Yet the expansion of renewables is still a huge challenge in terms of planning and operation, especially as new players, e.g., sector-coupling technologies, enter the energy markets. A timely energy transition, therefore, will also require reductions of energy demand through both sufficiency and efficiency measures. Solar photovoltaics (PV) are an essential part of this transition and the contribution of PV prosumers – households that produce their own electricity – is becoming increasingly relevant.

PV prosuming not only influences the electrical energy mix in the household, it can also lead to behavioral changes influencing energy consumption patterns (Dütschke et al. 2021; Galvin 2020). On the one hand, these changes can occur in the form of rebound effects, which we define in this context as *increases in energy consumption* subsequent to an increase in renewable energy use (Galvin et al. 2021). On the other hand, PV prosuming may result in *reductions in energy consumption*, which we understand as sufficiency-oriented behavior. Depending on the methodology and socio-technical variables used, studies focusing on rebound effects from PV prosuming find evidence for both trends, with a varying scope that can range from a reduction or no significant increase in consumption (Li et al. 2020; Oberst et al. 2019) to substantial rebound effects, potentially equivalent to the rate of self-consumption (Frondel et al. 2020).

The findings of the German research project *EE-Rebound* indicate increasing electricity consumption, especially for households that installed their PV-systems after 2011. This may be attributed to self-consumption becoming economically more profitable than grid feed-in after this date. Based on a survey among prosumer and non-prosumer households with a subsequent matching of their socio-technical characteristics, the post-2011 PV prosumer group was shown to exhibit an approximately 18 % higher electricity consumption than comparable non-prosumer households (Galvin et al. 2022).

The reasons leading to higher consumption can be manifold, but economic incentives play a crucial role. The currently low feed-in tariff may encourage a higher energy consumption, since households favor the maximization of self-consumption over feed-in remuneration (Galvin 2020, Weiß et al. 2021). The availability of equity financing with low ongoing costs can also encourage generous consumption. Prosumers practicing load shifting, i.e., moving power consumption into the sunny hours of the day when solar PV output is greatest, and those effectively using smart metering techniques are examples of energy-conscious behavioral changes in the other direction. Galvin (2020) and Dütschke et al. (2021) provide empirical findings on the significance of this prosumer group that comprehensively monitors energy consumption. Studies show that using extensive feedback systems can generally lead to decreases in energy consumption of 8 to 12 % (Dromaque and Grigoriou 2018; Gährs et al. 2021).

So far, the environmental implications of consumption changes in prosumer households remain uninvestigated. One could argue that household demand is largely met by PV output, with thus little or no environmental effect on either the household or the overall energy system. The goal of our research is to investigate the validity of this argument: how can we quantify the environmental effects of the changes in energy consumption patterns by PV prosumers and how relevant are these effects at household and system level?

First, we present the modeling of energy flows at household level and the upscaling to system level. Second, we elaborate the methods for environmental assessment in terms of greenhouse gas (GHG) emissions and apply these to the resulting energy flows and upscaling. Finally, we conclude with a summary and deduce recommendations for policy makers, civil society and prosumers with respect to increasing awareness of the importance of PV prosuming and its related consumption patterns.

Modeling of energy flows and upscaling scenarios

An examination of energy flows between a single household and the main grid is intended to help us investigate how the absence of energy sufficiency dampens the prosumer contribution to the energy transition. By upscaling the results of individual households to the system level in Germany, we provide insights into the overall effects of consumption patterns.

Method, input data, and scenarios

First, to investigate the effects on the grid exchange of a variety of consumption patterns, we rely on the IÖW Energy Prosumer Model. The model has been described in detail in Gährs et al. (2020). It provides a bottom-up simulation of energy flows in a household and allows us to simulate preset levels of electricity consumption based on a given household size and efficiency class (co2online 2022). We investigate the following scenarios for a 3-person and a 5-person prosumer household:

- *Reference (Ref):* Average consumption according to co2online (2022) (3-person household: ~3,700 kWh; 5-person household: ~5,200 kWh)
- *Sufficiency (S–10):* Reduced electricity consumption of approximately 10 %. We take this value as an average from the findings of the studies presented in the introduction.
- *Rebound (R+10; R+20):* An overconsumption of 20 % is chosen as an approximation of the aforementioned survey results of the project *EE-Rebound*. An overconsumption of 10 % is investigated as an intermediate step, since values on solar rebounds reported in the literature vary greatly.
- *Rebound and load shifting (R+10 & LS; R+20 & LS):* These scenarios encompass prosumers who, in addition to increasing their consumption, also practice load-shifting as described above.

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Second, we use available data to analyze the development of the German PV market and the share of small-scale PV prosuming systems with and without battery (AEE 2020; Bundesnetzagentur 2021; Figgener et al. 2021). We assume a dynamic growth for PV capacity of +0.7 GWp per year leading to approximately 140 GWp in 2030 (from ~60 GWp in 2021). While in line with other studies targeting 130 to 150 GWp (BDEW 2021; dena 2021), the capacity goal investigated here represents a moderate development of the PV market. This is emphasized by the recent draft for the amendment of the Renewable Energy Source Act (EEG), which targets 200 GWp by 2030 (BMWK 2022). Furthermore, we assume that PV prosuming < 100 kWp will almost quadruple compared to historical data.

Third, based on the average solar irradiation in Germany weighted by geographic distribution of the PV systems (DWD 2021) and our simulated energy flows for the various household sizes, we estimate the effect of different consumption patterns by PV prosumers across Germany. Further detailed assumptions can be found in Kegel et al. (2022).

Results and discussion

Results of the simulation at the household level show that overconsumption can only be partly met by self-consumption. Load shifting and battery storage can in part mitigate this demand, but with a more substantial increase in energy demand (e.g., R+20), the overconsumption has to be met largely by the grid. The described effects are presented in Table 1 for a 3-person household. Given that the results for a 5-person household are similar, they are omitted here, but can be found in our related paper (Lenk et al. 2022).

Results at the system level (including both 3- and 5-person prosumer households) indicate that upscaling the R+10 and R+20 scenarios lead to a comparably low effect on the current overall electricity demand in Germany (1.2 and 2.4 TWh in 2020, respectively). However, a significantly increased demand of 6 to 12 TWh is anticipated in 2030 (R+10 and R+20, respectively). In the case of the R+20 scenario, this translates to about 1.7 % of the forecasted electrical power demand for Germany in 2030 (BMWK 2022). Of this additional demand, 70 % would have to be grid-supplied. In contrast, if prosumers would tend towards more sufficient consumption patterns in the future (S–10), power savings of around –8.5 TWh could be achieved in 2030 (–2 TWh in 2020).

The potential aggravation of both sufficiency and rebound effects in 2030 is largely dependent on PV market development. Even a moderate development of the installed PV capacity, as assumed in our study, may result in the need for substantial additional renewable energy installations or longer operation of fossil-based power plants.

	Without battery storage		With battery storage	
	Self-consumption [kWh/a]	Grid supply [kWh/a]	Self-consumption [kWh/a]	Grid supply [kWh/a]
Ref	732	2,966	1,880	1,875
S–10	672	2,552	1,809	1,471
R+10	838	3,228	1,993	2,131
R+10 & LS	905	2,808	2,079	1,693
R+20	939	3,508	2,089	2,415
R+20 & LS	1,159	3,304	2,324	2,197

Tab. 1: Results of simulated self-consumption and grid supply for a 3-person household with a 3.5 kWp photovoltaic system, and 3.5 kWh battery: electricity fed into grid equals electricity produced (3,431 kWh in all scenarios) minus self-consumption. *Source: authors' own compilation*

Greenhouse gas emissions due to changes in energy consumption patterns

In the following, we first describe our methodological approach to determining GHG emissions at the household and energy system level. We then present and discuss the results.

Methods

To assess the climatic impact of changing consumption patterns at the household level, we carry out a life cycle assessment (LCA) based on international guidelines (DIN EN ISO 14044:2006). The system analyzed is the same PV prosumer household as described above. The system is compared to the various sufficiency and rebound scenarios, both with and without load shifting. System boundaries cover energy technologies and their life cycle, as well as energy flows from the grid. All energy and material flows and the resulting environmental impacts are related to our single household's power consumption for 2020 (i.e., the functional unit). The impact assessment is limited to climate change as impact category and the corresponding GHG emissions (CO_2eq) are according to the IPCC (2007) characterization factors.

For the impact assessment, we use three emission factors:

- *PV electricity:* 0.056 kgCO_2eq/kWh, derived from Lauf et al. (2021). The factor represents a generic device based on currently installed PV capacities in Germany.
- *Battery:* 12.195 kgCO_2eq/kWh of storage capacity and year, derived from Ökobaudat (BMI 2018). The value refers to a lithium iron phosphate battery system with a lifetime of 20 years.
- *Electricity from the grid:* 0.391 kgCO_2eq/kWh, based on Lauf et al. (2021) and on official statistics by AGEB (2021).

The factors for PV and battery include GHG emissions from peripheral equipment (e.g., cables, inverters); all factors are valid for 2020.

In order to investigate the changes in emissions of the entire German power sector, we apply two supply side approaches and the corresponding emission factors to the upscaled scenarios presented in the previous section:

- *Average generation mix (AGM):* The supply for additional consumption is equivalent to the average generation mix in a year. To depict past production mixes, we use official statistics by AGEB (2021). The 2025 and 2030 electricity mixes are based on Prognos et al. (2021). The actual implementation of such an approach would require an active response to changing consumption patterns by adjusting planned power plant expansions, especially with regards to renewable energies.
- *Natural gas power plants (NGPP):* Additional demand is provided by marginal generators in the German electrical power market. For practical reasons, we follow a common approach in life cycle modeling and assume natural gas turbines as single and constant marginal technology (Rehberger and Hiete 2015), which represents a strong simplification of market mechanisms. The approach is also relevant to actual changes in the German power plant fleet. Nuclear and coal

Scenario	Without battery		With battery	
	Emissions [$kgCO_2eq$]	cf. to Ref [%]	Emissions [$kgCO_2eq$]	cf. to Ref [%]
Ref	1,201	0	878	0
S–10	1,036	–14	716	–18
R+10	1,310	8	984	11
R+10 & LS	1,239	3	904	3
R+20	1,425	16	1,101	20
R+20 & LS	1,357	12	1,030	15

Tab. 2: Emissions for a 3-person household with a 3.5 kWp photovoltaic system (Ref is the scenario without behavioural changes). *Source: authors' own compilation*

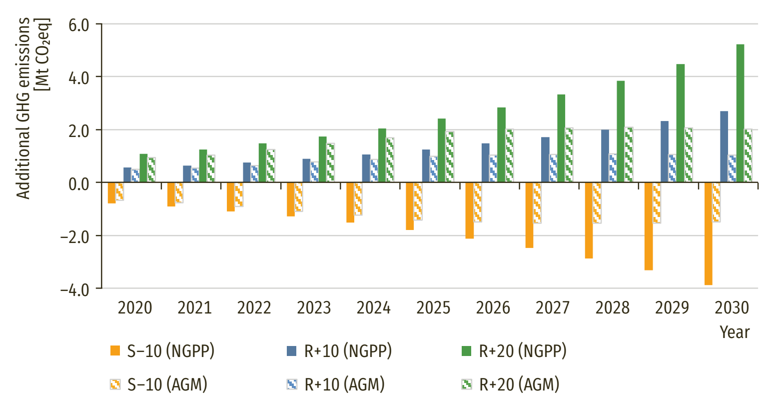

Fig. 1: Additional greenhouse gas (GHG) emissions per year until 2030; supply by natural gas power plant (NGPP) and by average generation mix (AGM). *Source: authors' own compilation*

power plants are to be phased out, whereas capacities of dispatchable gas power plants shall be expanded, according to the intentions of the current German government (SPD et al. 2021) and scenarios approved by the German Federal Network Agency (Bundesnetzagentur 2020).

Given that both approaches assess large-scale structural changes and consequences of two opposing options for decision-making, they conform to the approach of consequential life cycle inventory modeling (EC JRC IES 2010; Zamagni et al. 2012).

Technology-specific emission factors for electricity production including direct and indirect emissions of the upstream chains are taken from Lauf et al. (2021). The emission factors related to gross electricity production were adjusted for the power plants' own consumption. Furthermore, we neglect network losses and trade with neighboring countries.

The NGPP approach uses a fixed emission factor of 0.453 kgCO_2eq for each additional net kWh that is consumed. The emission factor in the AGM approach decreases from 0.391 kgCO_2eq/kWh in 2020 to 0.174 kgCO_2eq/kWh in 2030 due to the changes in the power plant fleet and electrical power production (our calculation based on Lauf et al. 2021; Prognos et al. 2021).

Results and discussion

An overview of the resulting GHG emissions at the household level is displayed in Table 2. Our 3-person household's GHG emissions for 2020 sum up to 1,201 kgCO_2eq (no battery) and 878 kgCO_2eq (with battery). Lower emissions with battery are due to the greater volume of PV self-consumption, which also overcompensates for additional emissions from battery production. Generally, the scenarios with rebound effects lead to higher GHG emissions both with and without battery when compared to the Ref scenario. In the sufficiency scenario, the household's GHG emissions decrease in both cases. Furthermore, a symmetrical rebound or sufficiency effect of 10 % leads to asymmetrical changes in GHG emissions (e.g., +8 and –14 % without battery), since changes in consumption have an effect on volumes of GHG-intensive grid supply rather than on PV self-consumption. With load shifting, emissions can be mitigated by up to eight percentage points.

In cases without battery, the emissions are mostly due to energy supply from the grid (~96 %) and to a lesser extent PV power supply (~4 %). In cases with battery, electricity from the grid remains the main source of GHG emissions (80–86 %), followed by PV (10–14 %) and the battery (~5 %).

Results for the impact assessment at the system level are shown in Figure 1 with the AGM approach, the S–10 scenario results in savings of 0.7 MtCO_2eq in 2020 and up to 1.5 MtCO_2eq in 2028. These savings remain at a similar level thereafter, since the yearly emission factor is falling towards 2030. Thus, decreasing consumption leads to less GHG savings per unit. Additional GHG emissions in the rebound scenarios peak in 2027 (R+10: 1.1 MtCO_2eq, R+20: 2.1 MtCO_2eq) and, subsequently, decline towards 2030 (1.0 and 2.0 MtCO_2eq, respectively) as the sinking emission factor overcompensates for the increase in electricity consumption.

The NGPP approach results in continuously decreasing emissions for the sufficiency scenario (S–10). Emissions of up to 3.9 MtCO_2eq in 2030 can be saved in 2030. In contrast, GHG emissions in the rebound scenarios are steadily increasing. In 2030, the additional burden sums up to 2.7 MtCO_2eq (R+10) and 5.2 MtCO_2eq (R+20).

The results show furthermore that load shifting has almost no effect on GHG emissions since we apply fixed emission factors per year, whereas this flexibility measure affects the household's power supply during the year.

Compared to the reduction target for the German energy sector in 2030 (108 $MtCO_2eq$ according to the Federal Climate Change Act, KSG (2021)), GHG emission savings due to a reduced energy demand (sufficiency) can account for a share of up to 1 % (AGM) and 4 % (NGPP). Additional emissions due to increased energy consumption (rebound effects) account for a share of up to 2 % (AGM) and 5 % (NGPP).

Since additional emissions fall toward 2030 in the AGM approach, our results might suggest that rebound effects become less of an issue over time. However, this conclusion neglects that the expansion of renewables is already becoming a challenge today. Therefore, additional GHG emissions in the case of overconsumption may impede climate targets, making a revision of consumption projections and renewables planning necessary.

Quantifying the degree of over- or underconsumption when a household turns prosumer, however, remains challenging. First, because empiric data on the behavioral effects of PV prosuming indicate cases of varying tendencies; second, because a clearer distinction between consumption associated with sector coupling vs. mere rebound effects is still pending. Upscaling magnifies these uncertainties further, as the same consumption patterns are applied to the entire German PV capacity < 100 kWp. This demands a more detailed investigation of consumption patterns with different PV system characteristics.

Using static, inner-annual emission factors of the average energy market mix or of marginal suppliers is common practice in LCA (EC JRC IES 2010; Rehberger and Hiete 2015). This approach, however, neglects dynamics in the power system. Lund et al. (2010) show that assuming natural gas power plants as a single marginal technology results in lower GHG emissions compared to a modeling approach that reflects dynamic market interactions. These dynamics are becoming even more relevant as volatile renewable energies enter the market. Furthermore, our impact assessment is limited to climate change, whereas other impact categories are also relevant for electrical power production (Barros et al. 2020). Finally, the actual changes in GHG emissions depend very much on the quantity and speed of renewable energy expansion and fossil fuel phaseout.

Conclusion and recommendations

Households tend to reduce their emissions when switching to prosuming (Lenk et al. 2022); this can be enhanced by sufficient behavior or diminished by rebound effects. As shown by our results at household level, greater energy consumption, triggered by prosuming, leads to greater GHG emissions. These can be mitigated by load shifting and the use of larger-sized PV systems, since, in both cases, the increased demand is more closely associated with the PV-produced electricity. In the defined sufficiency scenario, the results showcase decreasing emissions and a greater share of electricity fed into the grid.

The results of upscaling show that rebound effects can add up to relevant additional GHG emissions as the number of prosumer households increases and the politically intended market diffusion of PV and PV battery systems materializes. Load shifting can hardly reduce this effect, since the PV power used to meet the increased demand can no longer be fed into the grid.

Based on our analyses, we offer, in the following sections, recommendations to incentivize energy sufficiency and avoid rebound effects. We address measures to both encourage behavioral changes at the household level, as well as collective energy sufficiency strategies. Furthermore, tariffs and services are discussed. Finally, we present the needs identified for future research.

Information and consultation

Due to the fundamental importance of individual participation in the energy transition, it is key that we provide prosumers with the advice and information needed such that they can support climate goals with their consumption practices. In consultation, instead of focusing on self-consumption and the economic advantages of PV systems (Kratschmann and Dütschke 2021), the potential contribution of the prosumer to the energy transition should be emphasized more strongly.

Sufficiency-oriented behavior can furthermore be supported by real-time feedback on energy consumption. Smart meters can be used for this purpose, as they not only have a positive effect on power consumption, but are also economically and ecologically worthwhile (Gährs et al. 2021).

Political and regulatory framework

The Renewable Energy Sources Act (EEG) in Germany is currently fostering self-consumption among prosumer households as it is the most cost-effective option. This might be advantageous for acceptance and the fast expansion of solar PV. But it does not lead to sufficient consumption patterns, and often limits the size of the PV system being installed. As shown by Li et al. (2020), prosumer consumption tends to decrease, when feed-in increases; thus, increasing incentives for grid feed-in could support greater sufficiency-oriented behavior.

In addition, the EEG-rule, ensuring that small PV systems may feed in only 70 % of the rated power supports overconsumption, as some prosumers erroneously fear that up to 30 % of the electricity they produce, is "wasted" (Galvin 2020; Weiß et al. 2021). Targeted information on the actual low significance of this curtailment rule could reduce this problem.

Tariffs and services

Among the cloud and community tariffs identified in Lenk et al. (2022), some offer solutions to limit generous consumption. For instance, credit financing of the PV system with monthly installment payments can smooth out the uneven distribution between high initial investment costs and low ongoing operating costs of a

PV system. In addition, incentives like a cash-back system, where unused electricity quantities are paid out, can promote sufficiency-oriented behavior. (This, however, leads to additional household income, which, depending on how it is used, could lead to a monetary rebound and therefore to other ecological impacts.)

Further research

The environmental effects of changing consumption patterns as a consequence of becoming a prosumer household have so far not been addressed in energy system modeling, nor in climate neutrality trajectory planning. We urge further investigation of these linkages, e.g., by conducting more extensive interdisciplinary research and making scenarios with such behavioral effects a more common practice in modeling.

For the environmental assessment methods, future research could address models to investigate inner-annual dynamics in the power market. Further studies might also broaden the assessment to additional impact categories.

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DR. JAN KEGEL
studied renewable energy systems. He is involved in research projects investigating the technical aspects of decentralized energy systems.

Bildquelle: IÖW/Gordon Welters

JAN WIESENTHAL
has been researching in the field of energy prosumers and energy system modeling at the IÖW. He is currently also doing his PhD at Leuphana University in this field.

CLARA LENK
studied environmental engineering. The focus of her work at IÖW is mainly the ecological assessment of various aspects concerning the energy sector.

Bildquelle: IÖW/Gordon Welters

HANNES BLUHM
is a researcher at IÖW. His focus is on life cycle assessment and digitalization in the energy sector. He is currently pursuing a PhD at Europa University Flensburg.

Bildquelle: IÖW/Gordon Welters

DR. JULIKA WEISS
has led numerous projects dealing mainly with energetic refurbishment and climate-friendly heat supply. Rebound effects and consumer behavior have been focal points in recent years.

NESRINE OUANES
studied renewable energy systems with a focus on mathematical modeling. She works on decentralized electricity markets and their design instruments.

LUKAS TORLIENE
studied industrial engineering. He works on several research and policy consulting projects regarding climate and energy concepts as well as simulations and economic efficiency.

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A.6 Paper V (Bluhm et al., 2026): Assessing the environmental effects of digitally enabled, small-scale energy flexibilities: A consequential, multi-level life cycle approach

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Research paper

Assessing the environmental effects of digitally enabled, small-scale energy flexibilities: A consequential, multi-level life cycle approach

Hannes Bluhm [a,b],*, Clara Büttner [a,c], Ilka Cußmann [a,d], Jonathan Amme [d], Frauke Wiese [a]

[a] Europa-Universität Flensburg, Auf dem Campus 1, Flensburg, 24943, Germany
[b] Institute for Ecological Economy Research, Potsdamer Straße 105, Berlin, 10785, Germany
[c] Hochschule Flensburg, Kanzleistraße 91-93, Flensburg, 24943, Germany
[d] Reiner Lemoine Institute, Rudower Chaussee 12, Berlin, 12489, Germany

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ABSTRACT

The digitalization of small-scale energy technologies located in households is being increasingly promoted to enhance flexibility in future power systems with high shares of intermittent renewable energy sources. This study assesses the environmental impacts of such digitalization for Photovoltaic-Battery Storage Systems (PVBSs), Electric Heat Pumps (EHPs), and Battery Electric Vehicles (BEVs) in Germany's projected mid-term future energy system. Combining a multi-level, consequential life cycle assessment with the energy system model *eTraGo* and the associated *eGon2035* data set, we evaluate both direct impacts from Information and Communication Technology (ICT) and indirect effects from changes in power plant dispatch, large-scale flexibility expansion, grid expansion, and small-scale technology usage from two perspectives. From a system perspective, the results indicate that ICT-enabled flexibility reduces greenhouse gas emissions and other environmental impacts by improving how renewable energy is used. However, these benefits are accompanied by increased burdens in terms of mineral resource depletion, freshwater eutrophication, and ozone depletion, primarily due to the production and operation of ICT and EHPs. From a household perspective, flexibility decreases climate impacts for BEVs and EHPs but increases them for PVBSs, while mineral resource use rises across all technologies. Overall, intensified digitalization for flexibility is not a sufficient standalone solution for climate mitigation, but can contribute up to 8.5% of the remaining emissions gap to Germany's 2030 sector target, conditional on the underlying assumptions. Furthermore, it reveals a trade-off between environmental benefits and burdens. The findings highlight the need for complementary measures, circular strategies for ICT, and careful design of incentives to balance these trade-offs.

1. Introduction

Residential Photovoltaic-Battery Storage Systems (PVBSs), Electric Heat Pumps (EHPs), and Battery Electric Vehicles (BEVs) are three key electricity-based and decentralized energy technologies with the potential to decarbonize the heating, power, and mobility sectors. Consequently, capacities are expanding dynamically. For example, in Germany, the most populous country with the largest economy in Europe, the infrastructure regulation body, the Federal Network Agency, expects in its network development plan 2037/2045 that installed rated power of PVBSs will rise from 9.9 GW in 2024 to up to 80.9 GW in 2045, rated power of EHPs from 6.0 to up to 42.0 GW (assuming 3 kW per unit), and the stock of BEVs from 2.0 to 44.9 million (together with the corresponding charging infrastructure) (BNetzA, 2025a). Notably, PVBSs are already expanding dynamically as storage capacities more than doubled to 17.50 GWh from July 2023 to July 2025, whereas EHPs and BEVs are currently falling short of their targets (Roth and Schill, 2025). Similar developments with an expansion several times larger than the current plant portfolio are also expected on the European level until 2050 (ENTSO-E and ENTSOG, 2024).

On the one hand, this expansion mitigates greenhouse gas emissions when renewable energies have a high share in the power plant dispatch. On the other hand, the expansion of new loads and capacities poses challenges to the supply of electricity, as well as to the operation and expansion of power grid infrastructures. Therefore, the scale-up of

* Corresponding author at: Europa-Universität Flensburg, Auf dem Campus 1, Flensburg, 24943, Germany.
E-mail addresses: hannes.bluhm@ioew.de (H. Bluhm), clara.buettner@hs-flensburg.de (C. Büttner), ilka.cussmann@rl-institut.de (I. Cußmann), jonathan.amme@rl-institut.de (J. Amme), frauke.wiese@uni-flensburg.de (F. Wiese).

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Nomenclature

Units and indices

a	Year (*annum*)
CH4	Methane
disease incidences	Expected number of disease cases
el	Electric
eq	Equivalents
g	Gram
GB	Gigabyte
GW	Gigawatt
GWh	Gigawatt-hour
H2	Hydrogen
kBq U^{235}_{eq}	Kilobecquerel U^{235} equivalent
kg	Kilogram
kg CFC-11$_{eq}$	Kilogram trichlorofluoromethane equivalent
kg CO_{2eq}	Kilogram carbon dioxide equivalent
kg N_{eq}	Kilogram nitrogen equivalent
kg $NMVOC_{eq}$	Kilogram non-methane volatile organic compound equivalent
kg P_{eq}	Kilogram phosphorus equivalent
kg Sb_{eq}	Kilogram antimony equivalent
kW	Kilowatt
kWh	kilowatt-hour
MJ	Megajoule
mn	Million
mol H^{+}_{eq}	Mole hydrogen ion equivalent
mol N_{eq}	Mole nitrogen equivalent
MVA	Megavolt ampere
MW	Megawatt
MWh	Megawatt-hour
p	Piece/unit
TWh	Terawatt-hour

Impact category indicators

ADPf	Abiotic Depletion Potential (fossils) [MJ]
ADPm	Abiotic Depletion Potential (minerals) [kg Sb_{eq}]
AP	Acidification Potential [mol H^{+}_{eq}]
EPf	Eutrophication Potential (freshwater) [kg P_{eq}]
EPm	Eutrophication Potential (marine) [kg N_{eq}]
EPt	Eutrophication Potential (terrestrial) [mol N_{eq}]
GWP	Global Warming Potential [kg CO_{2eq}]
IR	Ionizing Radiation Human Health [kBq U^{235}_{eq}]
ODP	Ozone Depletion Potential [kg CFC-11$_{eq}$]
PM	Particulate Matter [disease incidences]
POCP	Photochemical Ozone Formation [kg $NMVOC_{eq}$]

Abbreviations

AC	Alternating Current
BEV	Battery Electric Vehicle
CLCA	Consequential Life Cycle Assessment
DC	Direct Current
EHP	Electric Heat Pump
eTraGo	electric Transmission Grid optimization
FU	Functional Unit
ICT	Information and Communication Technology
LCA	Life Cycle Assessment
PV	Photovoltaic
PVBS	Photovoltaic-Battery Storage System
PyPSA	Python for Power System Analysis

PVBSs, EHPs, and BEVs needs to be accompanied by the rollout of digital ICT to facilitate their flexible operation. Based on this, new digital services and business models are emerging, such as virtual power plants (Karami and Madlener, 2021) or dynamically priced electricity tariffs (Stute and Kühnbach, 2023).

However, research has shown that digitalized systems can lead to both intended and unintended positive and negative environmental effects at several levels. At the technology level, relevant effects include the product life cycle of digital technologies, encompassing production, operation, and the end-of-life phase, as well as the substitution of other appliances and optimization of processes. At the user level, environmentally relevant effects include changes in user behavior, such as rebound, induction, and beneficial effects. Furthermore, economy- and society-wide effects at the system level occur when a digital technology permeates markets on a large scale (Pohl et al., 2019). Therefore, the question arises as to how the environmental benefits and burdens of digitalized PVBSs, EHPs, and BEVs systems compare to one another, and whether their flexibilization actually meets the expectation of supporting the achievement of energy transition goals.

Although energy sector digitalization for flexibilization is being pushed by political decision-makers of the European Union and also in Germany, environmental concerns, considering the levels mentioned above, remain a marginal issue in technology assessments as they neglect the life cycle of the ICT involved and build on lump-sum assumptions regarding potential energy and infrastructure savings, and omit net analyses (cf. e.g., EY (2013), EY and BET (2024), Directorate-General for Energy (2015), Vitiello et al. (2022)).

In academia, Life Cycle Assessment (LCA) is a scientific and standardized method from environmental management that evaluates the "inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (DIN EN ISO 14040, 2006). It has already been applied to various digitalized systems and services, illustrating their potential impacts (see e.g., Arushanyan et al. (2014), Pohl et al. (2019)). However, comprehensive LCA studies assessing both benefits and burdens from digitalized PVBSs, EHPs, and BEVs are limited.

For BEVs, Wohlschlager et al. (2022) assess greenhouse gas emissions of infrastructures for uncontrolled, unidirectional, and bidirectional charging under past and future energy supply scenarios. Several studies have analyzed the effect of automation from different charging strategies under static national or regional supply mixes (e.g., Woody et al. (2021), Baumann et al. (2019)). Thus, they conduct an attributional LCA approach, which assumes a static environment and no effects of smart charging on the surrounding energy system. In contrast, another stream of studies focuses on the dynamic, system-wide impacts of smart charging on (future) energy supply mixes, i.e., they conduct a consequential LCA approach (e.g., Arvesen et al. (2021), Wohlschlager et al. (2024a,b), Xu et al. (2020), Rovelli et al. (2021), Tang et al. (2021b)). Typically, both types of study analyze the inner-annual (or hourly) electricity generation mix to make visible the short-term effects on and from smart charging of BEVs. Furthermore, Woody et al. (2021) and Xu et al. (2020) consider the environmental effect of smart charging strategies on battery lifetime.

For PVBSs, Fett et al. (2023) and Ren et al. (2021) address different battery charging and discharging strategies that involve the use of local energy management systems but no external parameters. In contrast, Tang et al. (2021a), Sun et al. (2019), and Vuarnoz et al. (2018) consider smart charging strategies that take into account external parameters, such as prices or hourly emission factors of grid-based power supply. Furthermore, Bluhm and Gährs (2023) analyze a PVBS being pooled in a virtual power plant and consider the effects of changes in battery life and a household's power supply, as well as the enabling effect of providing flexibility services in different power markets. Methodologically, they use historic, annual energy market mixes in an attributional LCA approach.

Furthermore, Teng et al. (2016) analyze the carbon impact resulting from flexible and non-flexible EHP and BEV, as well as combinations thereof, for the future UK power plant dispatch (thus following a consequential approach). In another example of EHP in Terlouw et al. (2019), the CO_2 emissions from energy management strategies in the residential energy system of a Swiss village with heat or electricity storage, including EHPs with shiftable loads, are determined.

Considering the spectrum of the literature mentioned above, the general direction of the study results is that digitally enabled small-scale flexibilities have a significant potential for greenhouse gas mitigation, both for households and national or supra-regional energy systems, due to improved alignment of loads and discharging with renewable energy availability. At the same time, when analyzed, the life cycle of the ICT involved is not negligible, and additional effects, such as technology usage and grid expansion, can both mitigate and exacerbate environmental impacts.

Reflecting on the state of LCA literature, as well as existing LCA reviews on digitalization in general (cf. Arushanyan et al. (2014), Pohl et al. (2019)) and on smart energy systems specifically (cf. Wohlschlager et al. (2023), Durillon and Bossu (2024)), we address three research gaps in this article. First, we intend to conduct a more comprehensive and net environmental assessment of the environmental effects of digitally enabled small-scale energy flexibility. Thus far, the focus on analyzed effects (which refers to the system boundaries) is different across studies. An integrated assessment across levels of impacts is typically not carried out (Durillon and Bossu, 2024). From the literature cited above, only two studies (Bluhm and Gährs, 2023; Wohlschlager et al., 2024b) cover both the product life cycle of ICT and further effects. Furthermore, only two studies (Bluhm and Gährs, 2023; Woody et al., 2021) address interactions between the level of indirect environmental effects of digitalized energy systems, such as the provision of system services on battery lifetime. Finally, only one of the identified studies (BEVs in Wohlschlager et al. (2024b)) considers additional or prevented grid expansion as an indirect environmental effect triggered by digitalized small-scale technologies, although LCA experts consider these to be highly relevant (Wohlschlager et al., 2023). The choice of scope and the absence of a net assessment can lead to under- and overestimation of environmental impacts.

Second, we suggest an LCA approach with equal analysis of PVBSs, BEVs, and EHPs. The existing body of LCAs is focusing more on isolated impacts of BEVs and less on digitalized PVBS and EHP systems or their interactions. Thus, the basis for strategic decision-making differs for the three technologies, and is not suitable for drawing conclusions about effects from parallel flexibility usage.

Third, we aim to apply the same methodological basis and conduct an impact assessment for a relevant set of impact categories. Existing studies build on different data, assumptions, and methodological choices. Thus, results are only comparable to a limited extent within and across technologies. Furthermore, in the impact assessment, the focus of the studies is on the global warming potential as the impact category. Other categories relevant to green energy technologies and ICT (e.g., mineral resource use (Yavor et al., 2021)) are not considered equally. This one-sided focus may lead to a narrow view of the environmental effects of digitalization and, ultimately, to decisions that trigger an unreflected shift of environmental burdens, such as from global warming to mineral resource depletion.

We intend to apply this approach to the following research question: What is the environmental impact of digitalization used for the flexibilization of small-scale energy technologies, specifically EHPs, PVBSs, and BEVs, in the future German power system? More specifically, we consider two analytical perspectives by addressing the following sub-questions:

- What is the environmental impact from the perspective of the entire German power system?
- What is the environmental impact from the perspective of households?

The goal of this article is to assess the environmental impacts of digitalized and decentralized energy flexibility from EHPs, PVBSs, and BEVs in the future German energy system on a consistent methodological basis covering both benefits and burdens. We have chosen Germany as the focus area for this study since the German power system is undergoing a profound transformation towards intermittent renewable energies on the supply side. An 80% share in electricity gross consumption is to be achieved by 2030 (EEG, 2023). Furthermore, electrification is being pursued on the demand side, backed by policies that aim for flexibilization with the aid of ICT. 90% of households with small-scale technologies shall be equipped with smart metering and control systems by 2032 (MsbG, 2016), compared to a level of 14.9% achieved by March 2025 (BNetzA, 2025b). The scope enables the assessment of large-scale diffusion effects at both the national and individual household levels. We focus on the effects of the product life cycle of ICT and optimization effects at the technology level, as well as the changes in power plant dispatch, large-scale flexibility expansion, and grid expansion needs as system-wide effects, and the interactions between these two levels. Furthermore, we aim to identify potential conflicts and synergies between the energy system and household perspectives. To achieve this, we conduct a consequential LCA for the two perspectives by integrating an energy system model that optimizes dispatch, grid expansion, and investment in large-scale flexibility options in the future German energy system.

In doing so, the article contributes to the existing scientific literature, as well as industry and policy knowledge, by proposing and demonstrating a methodological approach that enables a more comprehensive, precautionary environmental assessment of digitalization as one key strategic pillar of energy transition processes. The approach and analysis results reveal the overall relevance of ambitions of energy sector digitalization, unaccounted-for interactions, and potential trade-offs between impact categories (e.g., climate change vs. resource use), levels of effects (e.g., renewable integration vs. increased energy technology use), and perspectives (macro-scale system vs. individual household).

The structure of the article is as follows: Section 2 describes the methodological approach and covers the LCA phases of goal and scope definition and inventory analysis. Section 3 presents the results and discussion of the impact assessment. The article closes with the conclusion in Section 4.

2. Methods

To address this article's goal, we employ a multi-level, consequential LCA following ISO guidelines (DIN EN ISO 14040, 2006; DIN EN ISO 14044, 2006). Whereas attributional LCA assesses the potential environmental impacts of a system in a static context, a consequential LCA approach analyzes the effects of large-scale changes on surrounding markets as a consequence of a decision in the foreground system (EC, JRC, IES, 2010). We consider Consequential LCA (CLCA) to be an appropriate approach for the outlined research question, as the digitalization and flexibilization of several million units of PVBSs, EHPs, and BEVs have a significant impact on the surrounding macro-scale energy

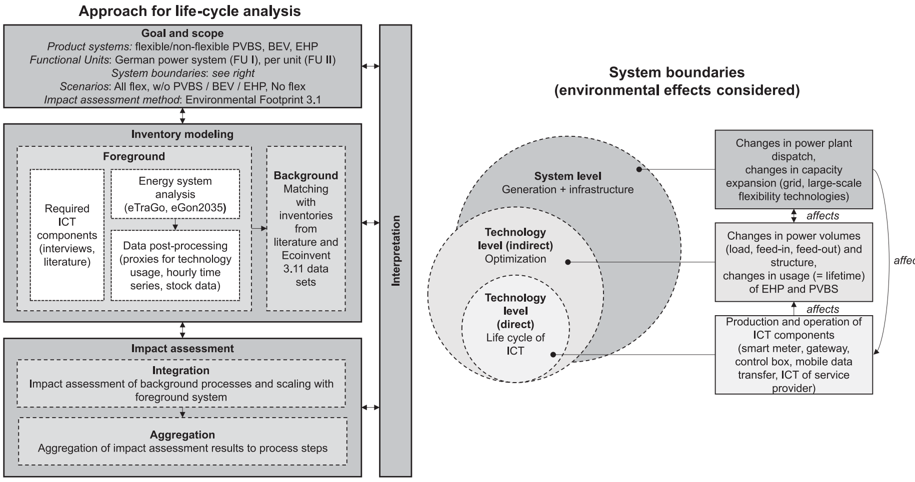

Fig. 1. Research approach
Source: Authors' own depiction based on DIN EN ISO 14040 (2006), Wohlschlager et al. (2023).

system. Furthermore, 'multi-level' refers to the interactions between the life cycle of ICT, the operation of energy technologies, and the macro-scale energy system.

We outline the research approach along the four LCA phases in Fig. 1. The following sections describe the methodological choices for the steps of goal and scope definition 2.1 and life cycle inventory modeling 2.3.

2.1. Goal and scope

The *goal* of the LCA is to assess the environmental benefits and burdens of digitalized, flexibly and non-flexibly operated PVBSs, EHPs, and BEVs at the technology and system level and to determine their net environmental impacts. One can understand the impacts as consequences of strategic decisions for or against the implementation of an intensified digitalization for flexibilization by decision-makers. Temporally, our analysis refers to a future German power system, reflecting the power plant fleet outlined in the German Network Development Plan (BNetzA, 2022), which results in a share of approximately 80% of renewable energies in electricity production volumes and a completed phase-out of coal-fired power plants. Thus, the results aim to support science-based decision-making on the strategic rollout of digitalization and flexibility facilitation in power systems with comparably high shares of intermittent energy sources.

The technological *systems under research* are PVBSs, EHPs, and BEVs in combination with wallboxes. The systems utilize electricity for space heating and hot water provision (EHP), mobility (BEV), or electricity storage (PVBS). Non-flexible systems follow local management strategies such as self-consumption optimization (PVBS), fixed user-driven (or 'uncontrolled') charging (BEV), or direct temperature-sensitive heating (EHP), where energy services are provided according to consumers' immediate demand and local conditions. Flexible systems make use of additional digital technologies to establish bidirectional communication with external entities that provide information and control signals (Meister et al., 2018), such as those based on grid conditions or current market prices via dynamic tariffs (cf. Nicolson et al. (2018)). Thereupon, the systems automatically adapt the load or adjust the discharging rate.

In the case of PVBSs and BEVs, operators make use of unused shares of the electrochemical storage capacities or by shedding charging and discharging rates. For EHPs, flexibilization can be achieved by installing a physical heat storage system or, to a lesser extent, by using the thermal inertia of the building's mass (Fischer and Madani, 2017).

To address the research questions, we define two *Functional Units (FUs)* to which the systems' inputs, outputs, and impacts are referenced:

- FU I: the German power supply for one year, and
- FU II: the electricity supply of a generic PVBS, EHP, and charging unit for a BEV for one year.

According to a taxonomy of environmental effects of smart energy systems drawn up by Wohlschlager et al. (2023), the *system boundaries* comprise the following environmentally relevant effects for FU I (see also Table 1): at the technology level, we consider the life cycle of ICT components in the household and for data transfer. In the flexible case, additional ICT components enable an external service provider (or 'aggregator') to manage external control. This results in changes in the energy technologies' used power volumes and their temporal structure, as well as in increased or decreased usage of PVBS and EHPs (optimization effects). The changes in loads, feed-in, and feed-out in turn generate effects at the system level by altering the structure of the power plant dispatch and the need for capacity expansion (power lines at 110–380 kV voltage levels, large-scale flexibility technologies). Effects resulting from changes in user behavior and substitutional effects are outside the scope of this analysis. An analysis of behavioral effects would go beyond the scope of this article. Substitutional effects could include the replacement of an analog electricity meter with digital meters. However, since we assume this replacement to apply in all scenarios, we do not associate the effect with the decision for or against flexibilization. For FU II, we have neglected the impacts from the expansion of large-scale flexibility technologies and grid expansion, since we assume that these are not of primary interest to households. Furthermore, environmental impacts from the power plant dispatch are accounted for by allocating them to the operational phase of the required ICT and the power offtake of the small-scale technologies. Finally, we apply system expansion for the discharging of PVBSs into the grid in the case of FU II. We assume that the generic unit substitutes for the average grid mix prevalent in an hour, and we account for this substitution as an environmental credit (see also Table 3).

We assess the energy sector as the primary affected market by the introduction of small-scale flexibilities. With reference to the guiding principles for CLCA by Weidema et al. (1999), we apply the consequential inventory modeling approach to short-term (operation) and longer-term (capacity expansions) changes in the broader (national) energy sector. In doing so, we consider the fact that there is not one single marginal supply technology but a portfolio of different technologies in the time-varying electricity supply mix (Lund et al.,

Table 1
System boundaries of FU I and FU II
p = production, o = operation.

Level of environmental effect	FU I (German power supply)	FU II (generic unit)
Technology level (direct)	Non-flexible: ICT in household and data transfer (p), Flexible: additional ICT in household (p), Flexible: additional ICT of external service provider and data transfer (p)	Non-flexible: ICT in household and data transfer (p, o), Flexible: additional ICT in household and data transfer (p, o), Flexible: additional ICT of external service provider and data transfer (p, o)
Technology level (indirect)	PVBS and EHP usage (p)	PVBS and EHP usage (p) power volumes and structure of PVBS, EHP, BEV (o)
System level	Power plant dispatch (o), capacity expansion of grid and large-scale flexibility technologies (p)	–

2010). Potential changes in the markets for ICT components and energy technologies themselves are outside the analysis's scope.

The system boundaries for foreground and background processes are defined from raw material extraction through fabrication to the factory gate ('cradle-to-gate'), plus the use-phase of the technologies involved. The dismantling and disposal of technologies are not within the system boundaries. This choice is justified by the comparative nature of the study: since end-of-life processes apply symmetrically across all scenarios, their exclusion does not affect the net differences between flexible and non-flexible configurations. Furthermore, the background data for energy technologies shall account for the combined provision of heat by power plants. Other potential multi-outputs of background processes are assumed to be negligible.

The system boundaries for foreground and background processes are defined from raw material extraction through fabrication to the factory gate ('cradle-to-gate'), plus the use-phase of the technologies involved. The dismantling and disposal of technologies are not within the system boundaries. This choice is justified by the comparative nature of the study: since end-of-life processes apply symmetrically across all scenarios, their exclusion does not affect the net differences between flexible and non-flexible configurations that are central to the research questions. Implementing cradle-to-grave boundaries, including material recycling or thermal treatment, could both increase and decrease impacts depending on the category, as discussed in Section 3.5.

For the *impact assessment*, we apply the Environmental Footprint 3.1 method (Andreasi Bassi et al., 2023; EC, 2021). Of the 16 impact categories, we focus on midpoint impact categories with a quality classification of level I ("satisfactory") and level II ("in need of some improvements") according to EC, JRC, IES (2011) for FU I: climate change or Global Warming Potential (GWP, in kg CO_{2eq}), Ozone Depletion Potential (ODP, in kg CFC-11_{eq}), Particulate Matter (PM, in disease incidences), Ionizing Radiation Human Health (IR, kBq U^{235}_{eq}), Photochemical Ozone Formation (POCP, in kg $NMVOC_{eq}$), Acidification Potential (AP, in mol H^{+}_{eq}), Eutrophication Potential (freshwater) (EPf, in kg P_{eq}), Eutrophication Potential (terrestrial) (EPt, in mol N_{eq}), Eutrophication Potential (marine) (EPm, in kg N_{eq}), Abiotic Depletion Potential (minerals) (ADPm, in kg Sb_{eq}), and Abiotic Depletion Potential (fossils) (ADPf, in megajoules (MJ)). In the case of FU II, we focus on GWP and ADPM impacts as categories that refer to the publicly discussed environmental issues that households are most likely aware of, i.e., climate change and critical resource use.

The inventory and impact assessment are implemented in the software SimaPro 10.2.

2.2. Scenarios

To analyze the environmental impact of digitalization in more detail, we define two main and three supporting 'what-if' scenarios according to which the life cycle inventory is modeled (see Table 2). All scenarios are based on the same envisioned power plant fleet and small-scale capacities outlined in the German Network Development Plan of the German Transmission System Operators (approved by the German Federal Grid Agency (BNetzA, 2022), i.e., exogenous variables; see Tables 3 and 4). In contrast, the dispatch and the expansion of large-scale flexibility-related technologies and grid capacities vary according to a cost optimization target (endogenous variables).

'*All flex*' depicts a development with sufficient ICT rollout that facilitates external control and flexible operation of small-scale technologies. In parallel, large-scale flexibility-related technologies (electrolyzers, hydrogen tank and salt cavern stores, fuel cells, methanation, steam methane reforming, and large-scale battery systems) and high-voltage and extra-high-voltage grid capacities (Alternating Current (AC) and Direct Current (DC)) are being expanded and operated in a cost-optimized manner. In contrast, '*No flex*' shows a path with fewer ICT components and the absence of flexibility from small-scale technologies. Thus, flexibility-related needs are met through changes in power plant dispatch, additional capacities of large-scale flexibility-related technologies, and grid expansion. In the supporting scenarios '*w/o EHP*', '*w/o BEV*', and '*w/o PVBS*', we analyze the impact of missing flexibilization from each small-scale energy technology. This approach enables an assessment of the relative importance of flexibilization among the three energy technologies in focus.

The configuration of the three small-scale technologies is provided in Table 3. The total installed capacities and number of installed units of the three small-scale technologies are based on the Network Development Plan and the scenario framework of the *eGon2035* data set (see Section 2.3). The capacity per generic unit and the assumed annual energy inputs are technical estimates based on the Network Development Plan, on findings from five supporting expert interviews with aggregators active in Germany (see also (Bluhm, 2025)), and on own assumptions that build on common energy industry figures. The energy reference streams define which energy mix is consumed, charged, and discharged. The stream is either the hour-specific grid mix or Photovoltaic (PV) electricity. Note that bidirectional charging of PVBSs can lead to negative environmental impact values if the charged mix is less impactful than the discharged mix.

2.3. Life cycle inventory

We now turn to descriptions of the life cycle inventory modeling. The first part depicts what digital components are assumed and inventoried, and how the energy system model is set up to capture system-level effects. The second part describes the handling of the system modeling outputs and the inventory data integration.

We provide a list of the foreground and background data used in Appendix A.

ICT inventory and energy system modeling assumptions

The foreground system comprises the required ICT components and the broader (national) energy system interacting with household-related energy technologies.

Table 2
Assumed control strategies and scenario configurations.

Category	Subcategory	EHP	BEV	PVBS	Large-scale flexibility and grid capacities[a]
Control strategy	Non-flexible (exogenous)	Temperature-sensitive load	User-driven charging	Self-consumption optimization	n.a.
	Flexible (endogenous)	External control	External control (uni-directional)	External control (bidirectional)	External control
Configuration of what-if scenarios	Dispatch				
	All flex	Flexible	Flexible	Flexible	Flexible
	w/o EHP	Non-flexible	Flexible	Flexible	
	w/o BEV	Flexible	Non-flexible	Flexible	Flexible
	w/o PVBS	Flexible	Flexible	Non-flexible	Flexible
	No flex	Non-flexible	Non-flexible	Non-flexible	Flexible
	Capacities (for all scenarios)	Exogenous	Exogenous	Exogenous	Endogenous

[a] Including electrolyzers, hydrogen tank and salt cavern stores, fuel cells, methanation, steam methane reforming, large-scale battery systems, high-voltage and extra-high-voltage AC and DC lines.

Table 3
Technology configuration and reference streams.

Category	EHP	BEV	PVBS
Total figures (configuration from or based on Network Development Plan)			
Total installed capacity	21,000 MW	68,267 MW[a]	16,800 MW
Total installed units in households	7.00 mn	6.21 mn (wallboxes)	3.36 mn
Per unit (configuration based on Network Development Plan, interviews, and own assumptions)			
Capacity per generic unit	3 kW	11 kW (wallbox)	5 kW (10 kWh; battery storage system)
Annual energy input per generic unit (non-flexible)	6,000 kWh	2,250 kWh	2,500 kWh
Energy reference stream non-flexible	Average grid mix per hour	Average grid mix per hour	PV in, average grid mix out per hour
Energy reference stream flexible	Average grid mix per hour	Average grid mix per hour	Average grid mix in, average grid mix out per hour

[a] calculated backward based on 15.1 mn BEVs according to the Network Development Plan (German TSOs, 2021), of which 41.1% are assumed to have access to private charging points in households with installed wallbox according to the vehicle simulation (see 2.3).

Based on German regulations, we assume that households with non-flexible energy technologies require one digital meter and a communication gateway. A data transfer of 0.25 GB occurs for measuring, billing, and accessing information in the customer portal. In flexible cases, we assume the following communication architecture: an external entity (e.g., an aggregator or distribution system operator) receives measured data from two digital meters via a communication gateway, processes the data with its data center capacities, and sends control signals via the gateway to a control box for changes in load, feed-in or feed-out (for more details see e.g., Meister et al. (2018)). The data transfer totals approximately 1.45 GB via mobile transmission standards. We base the concept on supporting interviews with German aggregators (cf. Bluhm (2025)) and on actual measuring concepts by market players (cf. VBEW (2024)).

Inventories for the ICT components stem from peer-reviewed secondary literature. We match material and energy requirements for production with corresponding data sets of the Ecoinvent 3.11 cutoff database (Wernet et al., 2016).

Alongside the ICT component inventory, the foreground system modeling draws on energy system analysis to evaluate the system-level effects of changes in dispatch and infrastructure requirements. For this, we apply the open-source energy system *electric Transmission Grid optimization (eTraGo)* together with the *eGon2035* data set (eTraGo Developer Group, 2023b,a), which builds upon the *Python for Power System Analysis (PyPSA)* framework (Brown et al., 2017).

eTraGo is a partial equilibrium model that simulates and optimizes the dispatch and expansion of a sector-coupled energy system under least-cost principles and technical constraints. The core optimization is conducted via a Linear Optimal Power Flow, enabling integrated investment and dispatch decisions. As in previous studies using *eTraGo* for the German context (Büttner et al., 2024; Esterl et al., 2024), our application reflects a mid-term future scenario with substantial capacity and load increases in the electricity system, based on assumptions from the German grid development plan (German TSOs, 2021). Central parameters of the applied energy system model are listed in Table 10 in the appendix. Further information on the model assumptions are given in Büttner et al. (2024). The spatial scope encompasses the German high-voltage and extra-high-voltage transmission grid, while distribution-level infrastructure below 110 kV is excluded. Temporal granularity is reduced to every fifth hour to manage computational complexity, while still capturing critical system dynamics. An extensive documentation of the modeling approach is included in Büttner et al. (2024), which also includes sensitivity analysis.

The model does not simulate explicit market mechanisms, control strategies, or business models. Instead, it assumes a system-optimal dispatch and expansion from a macroeconomic point of view. We have not integrated impacts from downstream environmental effects (i.e., ICT production) into the optimization process. Life-cycle impacts from power plant dispatch, large-scale flexibility expansion, and grid expansion are assessed ex post based on modeled outputs (cf. Blanco et al. (2020)).

To build a life-cycle inventory for the energy system, the modeled energy output of each power plant type of the *eTraGo* model is matched with a corresponding Ecoinvent data set. We adjusted the data sets to exclude the construction and disposal of power plants, focusing solely on operational data for the assessment, as the exogenous power plant fleet is the same across all scenarios and is not part of the decision-making process for or against flexibilization. Furthermore, for consistency, we adjusted the data sets according to assumed conversion efficiencies of the *eGon2035* data set.

In the energy system analysis, we model decentralized flexibility options by contrasting flexible and inflexible variants of selected technologies as described in Table 2. We proceed as follows:

- In the non-flexible case, *PVBSs* operate according to an optimization strategy that maximizes the self-consumption of PV generation at each high-voltage/medium-voltage substation. This additional optimization step is applied to all distribution grids associated with these substations individually. In total, the model comprises more than 3800 high-voltage/medium-voltage substations. In the flexible case, the storage units are dispatched system-optimally without local constraints. To model the effects on the lifetime of PVBSs, inventory data for a lithium-iron-phosphate battery system are sourced from the Ecoinvent database. The total number of load cycles is assumed to be 10,000.
- *BEVs* are modeled with unidirectional, flexible charging strategies in the flexible case. In inflexible scenarios, charging is fixed and user-driven. While bidirectional charging would offer greater flexibility, it has not been included due to practical limitations: current German regulations and industry interviews suggest that widespread bidirectional charging before 2030 is unlikely (see also Bluhm (2025)). We model the charging behavior of BEVs, including fully electric and plug-in hybrid vehicles, based on hourly availability profiles. Driving and parking profiles are simulated using the open-source tool *SimBEV* (Reiner Lemoine Institut, 2022). Flexibility potentials are determined using the tool *eGon-data* (eGon-data Developer Group, 2022), accounting for constraints such as state-of-charge levels and available charging power. The central assumption is that 80% of private charging events at home and 50% at work can be flexibilized.[1]
- We model the flexible operation of *EHPs* through virtual thermal storage capacity, enabling temporal decoupling of electricity use and heat demand for up to 3.5 h. We have not explicitly assumed a physical storage or the use of thermal inertia of buildings. In the inflexible case, EHPs are modeled as temperature-sensitive loads with no load-shifting potential. As background data for EHPs, we use an Ecoinvent dataset for an air–water EHP. The total operating hours are assumed to be 40,000, according to the Ecoinvent documentation.

At the system level, endogenous capacity expansion is allowed for selected large-scale flexibility-related technologies and grid capacities. At the same time, the Network Development Plan (German TSOs, 2021) serves as the basis for exogenously setting the remaining technology capacities. Through this scenario-based approach, we isolate the effects of flexible behavior by comparing identical system assumptions with and without flexibility integration. Life-cycle inventories for the construction and operation of large-scale flexibility-related technologies, as well as the construction and maintenance of grid infrastructures (including alternating and direct current lines), are sourced from secondary literature (see Appendix).

Energy modeling results, post-processing, and model integration

The energy modeling results include power plant dispatch, imports to and exports from the German power system, and the endogenous expansion of large-scale flexibility-related technologies and grid capacities. We provide result data as supplementary material in a dedicated Zenodo repository (see Data Availability section). Endogenous results of the German power plant dispatch, as well as large-scale flexibility, grid expansion capacities, and small-scale technology usage as intermediate outputs used for the inventory modeling, are provided in Tables 4, 5, and 6. Aggregated results for the domestic energy supply are provided in Fig. 2.

Using the time series with every fifth modeled hour of the *eTraGo* model, we determine an inner-annual national dispatch (power generation in Germany plus country-specific imports minus general exports). Furthermore, time series for aggregated loads, feed-in, and feed-out of EHPs, PVBSs, and BEVs are prepared, as well as per generic unit.

Since the *eTraGo* model does not provide a method for deriving the number of compressor starts for the EHP fleet, we use the aggregated full-load operating hours as a proxy for technology usage. For PVBSs, we determine and use the aggregated number of full-load cycles.

Finally, we sum up endogenous one-off effects, i.e., the expansion of large-scale flexibility-related technologies (in megawatts of energy input or output, or megawatt-hours of capacity) and grid capacities (in megavolt amperes).

We establish a soft link in which the post-processed data of the energy system model is multiplied by the impact assessment data of the adjusted inventory data sets. The integrated model provides impact assessment results for each impact category and for each of the two FUs.

3. Results and discussion

The following Sections 3.1 and 3.2 present the impact assessment results and discuss them per FU. Section 3.3 discusses potential conflicts between the system and households' perspectives, followed by a reflection in the light of the current industry and policy context in Section 3.4. Finally, we discuss the analysis's limitations in Section 3.5.

3.1. FU I: German power system

Fig. 2 presents the results of the environmental impact assessment for the eleven impact categories of FU I. For each impact category, the overall result of the *All flex* scenario serves as the benchmark (100%) for all process stages across all scenarios. Furthermore, Fig. 2 displays absolute values of the *All flex* scenario per category above the respective columns.

For orientation, the Figure also displays the electricity volumes provided for domestic consumption, which amount to about 762 TWh and import shares of approximately 38%.

Except for ADPm, the results fall within a corridor of 97.0% to 102.2%. With ADPm, the range extends from 61.9% to 102.2%. The *w/o PVBS* scenario achieves the lowest impact in eight of eleven impact categories (all except ADPm, EPf, and ODP). In these eight categories, *w/o PVBS* is followed by *All flex* (difference of up to 0.3 percentage points). For the remaining impact categories, *No flex* (ADPm), *w/o EHP* (EPf), and both scenarios together (ODP) achieve the lowest impacts, with percentages of 61.9%, 97.0% and 98.0%, respectively.

Electricity production for domestic supply and imports together account for the largest share of impacts across all categories except ADPm, with values ranging from 64.2 (ODP) to 100.5% (ADPf). The absence of ICT-enabled flexibilization of small-scale technologies results in a higher renewable energy curtailment (not displayed) of 6.1 TWh (*No flex*) compared to 5.7 TWh (*All flex*), thereby reducing the need for domestic power production from conventional power plants. In other words, digitalization enables greater flexibility, resulting in a higher energy yield from existing renewable energy capacities, which is environmentally beneficial. The import consistently causes more burdens (at least 90% more) than domestic production. This is due to the structure of the power plant dispatch in other countries, which

[1] Private charging at home accounts for 32.7% of the total energy demand of BEVs, and charging at work accounts for 10.4%. The remaining demand is public charging, assumed to be inflexible.

Table 4
German generation capacity (exogenous) and dispatch (endogenous).

Carrier	Capacity (GW)	Dispatch (TWh) All flex	w/o PVBS	w/o BEV	w/o EHP	No flex
Gas	50.1	48.6	48.6	47.7	47.7	52.6
Oil	0.3	0.2	0.2	0.2	0.2	0.2
Others	0.8	7.0	7.0	7.0	7.0	7.0
Reservoir	0.4	2.3	2.3	2.3	2.3	2.3
Run-of-river	4.4	25.1	25.1	25.1	25.1	25.1
Solar ground-mounted	35.9	41.4	41.4	41.4	41.4	41.4
Solar roof-top	84.1	96.6	96.6	96.6	96.6	96.6
Wind offshore	34.0	152.7	152.8	151.2	151.7	150.7
Wind onshore	90.9	273.5	273.5	273.5	273.5	273.3
Biomass	8.6	14.3	14.3	14.8	14.4	14.8
Sum	300.9	647.4	647.4	645.0	645.5	649.2

Table 5
Expansion of large-scale flexibility and grid capacities (endogenous).

Technology	Unit	All flex	w/o PVBS	w/o BEV	w/o EHP	No flex
Hydrogen tank stores	MWh	58,735	58,750	60,215	60,919	64,268
Hydrogen salt cavern stores	MWh	836	1351	97	167	1225
Steam methane reforming	MW_{H2}	3631	3651	3459	3577	3274
Methanation	MW_{CH4}	10,663	10,699	10,763	10,841	11,080
Fuel cells	MW_{el}	3	4	0	1	3
Electrolyzers	MW_{el}	22,853	22,901	23,066	23,139	23,603
Large-scale battery systems	MWh	3796	3796	3796	3796	3796
AC lines	MVA	1,403,446	1,403,570	1,406,575	1,406,781	1,411,598
DC lines	MVA	24,251	24,213	23,974	24,052	23,803

Table 6
Technology usage of PVBSs and EHPs per scenario
Minor differences between the *No flex* and the technology-specific scenarios occur due to clustering and averaging methods in the eTraGo model.

Technology	Unit	All flex	w/o PVBS	w/o BEV	w/o EHP	No flex
PVBS	mn full-load cycles	1,170	1,552	1,297	1,156	1,625
EHP	mn full-load hours	4,223	4,229	4,244	3,893	3,866

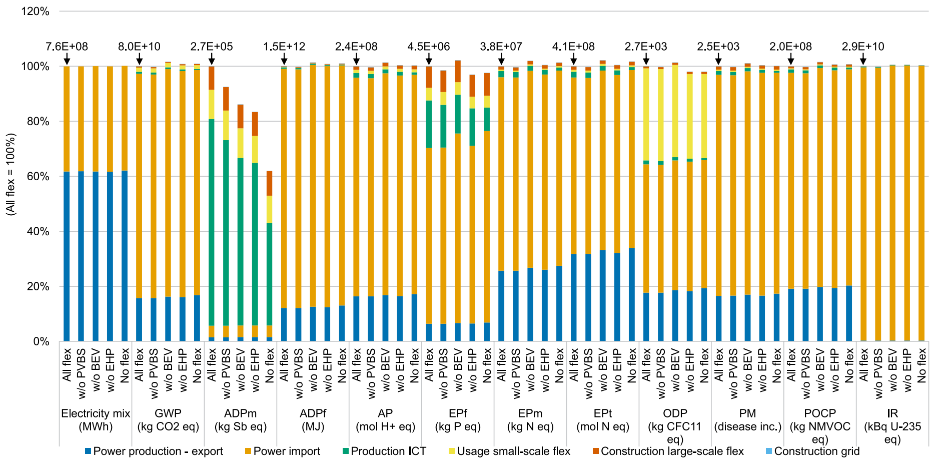

Fig. 2. Energy system modeling and impact assessment results for FU I (German power system).
The values above the columns represent the absolute results of the *All flex* scenario in the respective impact category.

contains larger shares of power volumes from conventional power plants (i.e., fossil fuel-fired plants, particularly coal-fired plants, and nuclear plants).

The production of ICT is particularly relevant for ADPm (37.2–75.1%) and EPf (8.6–17.3%) impacts. More specifically, 31.2% to 62.4% of the total ADPm burdens are attributed to the production of metering devices. Here, gold is primarily used in the manufacture of active electronic components, including diodes, transistors, and integrated circuits. The required smart meters also account for 7.1 to 14.1% of the total EPf impact, primarily due to phosphate emissions into water compartments during extraction and production processes. The production of the gateway and control box exhibits effects similar to those of the metering devices, but at lower levels. Data transfer and the ICT equipment of service providers together do not cause more than 0.8% of total ADPm and 0.2% of EPf impacts.

Except for ADPm, EPf, and ODP, the impact of the usage of small-scale flexibility technologies does not exceed 1.6%. 9.1 to 10.0% of overall ADPm impacts, 3.9 to 4.3% of EPf impacts, and 30.6 to 33.5%

of ODP impacts originate from the use of EHP. In scenarios with EHP flexibility, the full-load hours increase up to 9.8% compared to inflexible scenarios (see Table 6), and thus, resulting impacts increase by the same magnitude. The main contributors are tellurium and copper used (ADPm), as well as phosphate and phosphorus emissions into water (EPf), both of which occur during the production of the EHP devices, as well as the production of the assumed R134a refrigerant (ODP). On the other hand, flexibilization reduces the number of full-load cycles of PVBS. However, their share in overall ADPm, EPf, and ODP impacts does not exceed 0.8%.

Increased ICT-enabled small-scale flexibility tends to reduce the need for large-scale flexibility, resulting in lower environmental impacts from their expansion and operation. However, changes in impacts are relatively small compared to the overall impacts. The expansion of large-scale flexibility technologies leads to impacts of up to 1.3% in categories besides ADPm and EPf. ADPm impacts range from 8.5 to 8.9%, and EPf from 7.8 to 8.3%. The highest ADPm shares result from the construction of capacities for electrolyzers (~6.1%) and hydrogen overground storage systems (~1.8%). Here, the primary need is for gold, silver, and tellurium for the electronics of the electrolyzer, which drives the use of abiotic resources. Phosphate emissions to water cause the main EPf impact and stem from electronics production for the electrolyzer and steel usage for the hydrogen overground storage construction.

Impacts from AC and DC grid expansion do not exceed 0.1% in any category. Hence, the absolute impacts from grid expansion, as well as changes caused by small-scale energy flexibilization, are negligible compared to the other process stages and overall impacts.

As for the relevance of the three small-scale energy technologies, the comparison to the *All flex* scenario reveals the following relationships:

- BEV: Measured against the resulting environmental impact, BEVs stand out. In nine impact categories (all except ADPm and PM), the lack of flexibility from BEVs results in even higher environmental impacts than the *No flex* scenario. The greater relevance of BEVs can be explained by the comparably high ratio of average BEV battery capacity to the rated power of a wallbox (about 5 to 7 h), the large number of units, and thus, the high cumulative flexibility potential.
- EHP: Missing flexibility from EHPs decreases environmental (ADPm, EPf, ODP) and increases (remaining categories) environmental impacts. Furthermore, lower differences in changes compared to the missing flexibility of BEVs can be explained by the assumed lower ratio of (heat) storage capacity to the rated power per unit (ca. 3.5 h) and the seasonality of EHP loads.
- PVBS: A missing flexibilization of PVBS tends to have a decreasing effect on environmental impact in several impact categories. This is because the additional flexibility potential is not sufficiently utilized to compensate for the additional environmental burden of extra ICT elements. Furthermore, the ratio of PVBS capacity to rated power (2 h) and the cumulative rated power are the lowest among the three technologies.
- *No flex*: Not facilitating flexibility from small-scale energy technologies requires the expansion and operation of large-scale flexibility-related technologies, as well as a change in the power plant dispatch, but it also reduces the need for ICT elements. In summary, this scenario results in both lower (ADPm, EPf, ODP) and higher (remaining categories) environmental impacts.

In addition, Table 7 displays the absolute and specific GWP results of the power supply. The specific values range from 101.9 to 103.9 g CO_{2eq}/kWh (taking into account exports and imports) and 28.9 to 30.3 g CO_{2eq}/kWh (domestic production only), respectively. Furthermore, the Appendix contains additional results, including the life cycle of the exogenous power plant fleet. We refer to the additional results in the discussion for a better understanding of our findings within the broader environmental context of the German energy transition.

When all the results for FU I are taken together, the results show that the ICT-enabled flexibilization of small-scale energy technologies in the German power system leads to both environmental benefits and additional burdens — depending on the process stage, the flexibilized energy technologies used, and the impact category under consideration.

Regarding power plant dispatch, the flexibilization of small-scale technologies increases the share of renewable energies. Furthermore, increased ICT-enabled small-scale flexibility tends to reduce the need for large-scale flexibility, resulting in lower environmental impacts from their expansion and operation. However, changes in impacts are relatively small compared to the overall impacts. The impacts of grid expansion are negligible in comparison to the overall burdens. However, additional direct effects of digitalization for flexibilization (additional ICT components) are not negligible. Although indirect effects tend to outweigh or overcompensate direct effects in eight of eleven impact categories, this is not the case for ADPm, EPf, and ODP. Thus, increased digitalization leads to a shift in burdens towards these three environmental impact categories. Furthermore, increased small-scale flexibility comes at the cost of a rise in full-load hours of EHP. On the other hand, flexibilization may be beneficial because it would reduce the number of full-load cycles of PVBS. The shortened EHP lifetime is relevant for ADPm and ODP impacts. However, the changes in impacts compared to the overall impacts are somewhat limited.

To assess the relevance of the changes in emissions, we compare the GWP figures to the German greenhouse gas emission target for the energy sector of 175 Mt CO_{2eq} in 2030 (KSG, 2019). The budget includes direct emissions from public power and heat production, as well as energy infrastructure. The sector's emissions totaled 185 Mt CO_{2eq} in 2024 (UBA, 2025). Thus, a gap of approximately 10 Mt CO_{2eq} remains to meet the 2030 target. Although different system boundaries apply in our analyses, the maximum absolute difference of the *No flex* scenario compared to the remaining scenarios of 0.8 Mt CO_{2eq} for domestic production (see Table 7) illustrates the scale of potential emissions reduction due to flexibilization. Thus, digitalization for flexibilization could reduce the 2024 emission level by 0.5% and its contribution to closing the gap to the 2030 target could be approximately 8.5%,[2] which is an upper bound under optimal dispatch conditions and conditional on the underlying assumptions. Under real-world constraints (potentially slower smart meter infrastructure rollout, limited user activation), the figure would be lower. In the event of a fossil power plant phase-out that is slower than planned, controllable small-scale systems might have a greater impact on emissions reductions.

To discuss the relevance of results in other impact categories, we refer to the additional results in Appendix A. Fig. 4 includes the construction of the exogenously defined power plant fleet. Consequently, the impact shares the remaining environmental effects considered in the system boundaries decrease as the shares of power import and domestic power production (excluding export shares) increase. More specifically for the *All flex* scenario, ADPm impacts are 8.4 times as high once construction is taken into account, and the share of ICT production decreases from 75.1% to 8.9%. Total EPf impacts increase by a factor of 5.3, with the share of the production decreasing from 17.3% to 3.3%. ODP impacts increase by a factor of 1.4. Here, the share of the usage of small-scale technologies, as the most relevant process step beyond power provision, decreases from 33.4% to 6.9%. Thus, the direct environmental impacts of digitalization and the resulting indirect changes become many times smaller when considered in the context of the power system's overall impact. Nevertheless, the burdens remain salient and are triggered by the life cycles of mostly new ICT devices and small-scale technology usage.

[2] The figure is calculated as follows: $\frac{19.0\ \text{Mt CO}_{2\text{eq}}(\text{domestic production } No\ flex) - 18.2\ \text{Mt CO}_{2\text{eq}}(\text{domestic production } w/o\ PVBS)}{185\ \text{Mt CO}_{2\text{eq}}(\text{emission level 2024}) - 175\ \text{Mt CO}_{2\text{eq}}(\text{emission target 2030})} = 8.5\%$ of emission gap.

Table 7
GWP of electricity generation in Germany.

	Unit	All flex	w/o PVBs	w/o BEV	w/o EHP	No flex
Domestic production - Export + Import						
Energy volumes	TWh	762.2	762.1	762.9	762.0	763.3
Emissions	Mt CO_{2eq}	77.9	77.7	79.3	78.7	78.9
Emission factor	g CO_{2eq}	102.1	101.9	103.9	103.3	103.4
Domestic production						
Energy volumes	TWh	629.3	629.3	629.4	629.1	629.5
Emissions	Mt CO_{2eq}	18.2	18.2	18.8	18.6	19.0
Emission factor	g CO_{2eq}	29.0	28.9	29.8	29.5	30.3

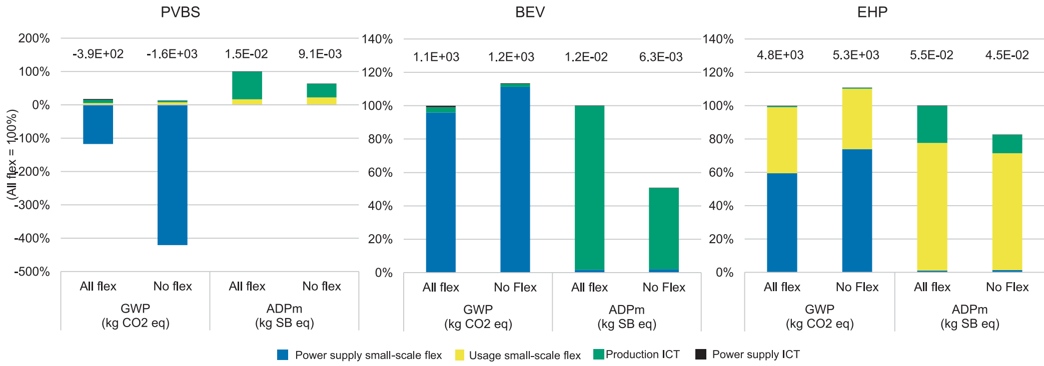

Fig. 3. Impact assessment results for FU II (generic unit).

The differences in the GWP of the *All flex* and the *w/o BEV* scenarios of 1.4 Mt CO_{2eq} (absolute) and 1.7 g CO_{2eq}/kWh (specific) (see Table 7) are in line with Wohlschlager et al. (2024a), who report differences of 0.9 Mt CO_{2eq} and 1 g CO_{2eq}/kWh between a reference and a bidirectional charging scenario in 2030. Major differences from our figures are due to the scenario design (availability of parallel flexibility options) and the assumed power plant fleet. Other studies are less comparable to our results due to differences in the geographic and temporal scope (i.e., they do not refer to Germany in the mid-term future) and the approach of linking LCA and energy system modeling (endogenous instead of ex-post integration). However, Xu et al. (2020), Wohlschlager et al. (2024b), and Arvesen et al. (2021) support our general findings that the energy system's GWP impacts decrease with increasing flexibility from BEVs.

3.2. FU II: Power supply of a generic unit

Fig. 3 shows the GWP and ADPm results per generic PVBS, BEV, and EHP unit for the modeled year. Again, the *All flex* scenario serves as the benchmark (100%) for all process stages and also provides the benchmark for the *No flex* scenario. To highlight significant differences, we present only the results of the two main scenarios.

Across the three technologies, GWP results are both higher (EHP, BEV) and lower (PVBS) in the *No flex* scenario than in the *All flex* scenario. In contrast, ADPm results are lower in the *No flex* scenario for all three technologies.

Regarding the PVBS in the *All flex* scenario, GWP results are -3.9E02 kg CO_{2eq}. Negative values originate from the charging in hours with less carbon-intensive energy mixes and the discharging in times with more carbon-intensive energy mixes. −117.4% of the impact goes back to the power supply of the unit, 9.4% stems from the production of ICT, 5.9% from the usage of the battery storage system, and 2.2% to the power supply of the required ICT. The result of the *No flex* scenario is −1.6E03 kg CO_{2eq}, or −407.7% compared to the *All flex* scenario. Impacts split into the unit's power supply (−420.7%), the usage of the PVBS (8.1%), the production of ICT (4.6%), and the power supply of ICT (1.0%). The ADPm in the *All flex* scenario is 1.5E−02 kg SB_{eq}. This is dominated by the production of ICT (83.1%), the usage of the battery storage system (16.0%), and the unit's power supply (1.0%). The ADPm level of the *No flex* scenario is 61.8% of the *All flex* scenario. Impacts mainly split into the production of ICT (41.1%), the usage of the storage system (22.1%), and the unit's power supply (−1.4%).

For the BEV, the GWP in the *All flex* scenario amounts to 1.1E03 kg CO_{2eq}. 95.8% results from the charging power supply of the BEV, 3.4% from the production of ICT, and 0.8% from its power supply. The overall *No flex* impact is 13.5% higher. 111.4% stems from the charging power supply, and 1.7% from ICT production. The remainder of the life cycle stages is negligible (< 0.4%). ADPm impacts amount to 1.2E−02 kg Sb_{eq}. These split into the production of ICT (98.4%) and the power supply of the BEV unit (1.6%). The ADPm impact of the *No flex* scenario accounts for 50.7% of the *All flex* scenario (or 6.3E−03 kg Sb_{eq}). Again, the production of ICT is the primary contributor (48.7%), followed by the power supply of the BEV (2.0%).

Annual GWP results for the generic EHP unit are at a level of 4.8E03 kg CO_{2eq}. The primary sources of impact are the power supply of the EHP unit (59.5%), the technology usage (39.6%), and the production of ICT (0.8%). Overall GWP impacts are at a level of 110.7% (or 5.3E03 kg CO_{2eq}) in the *No flex* scenario. These consist of impacts from the power supply of the EHP unit (74.0%), the technology usage (36.3%), and the production of ICT (0.4%). The *All flex* scenario yields an APDm result of 5.5E−02 kg Sb_{eq}. The breakdown reveals shares of 76.5% for the usage of the EHP unit, 22.4% for the production of ICT, and 1.1% for the power supply of the unit. In contrast, the overall ADPm impact of the *No flex* scenario is 82.6% of the *All flex* scenario. The distribution includes 70.0% from the usage of the EHP unit, 11.1% from the production of ICT, and 1.5% from the power supply of the generic EHP unit.

In terms of the relevance of the life cycle stages across small-scale technologies, we observe the following:

- Direct GWP and ADPm impacts from ICT production and operation practically double due to the additional digital equipment in the *All flex* scenario. ICT production and operation are responsible for 11.1% (EHP) to 98.4% (BEV) of the total ADPm impact, but less for total GWP impacts (0.4–11.5%). Moreover, production is causing several times more impacts than the operation. Thus, the relative impact of ICT is different for the three technologies' owners, and it is particularly relevant for mineral resource use.

- The power supply of the generic unit is repsonsible for the primary share of the GWP impact, which changes by values of 15.6 (BEV) to 303.3 (PVBS) percentage points between the two scenarios. Changes are due to one overarching effect: a change in the structure of power supply that becomes less or more GWP-intensive through flexibilization. Furthermore, technology-specific changes apply. For PVBS, the modeled power supply changes from own-supply with electricity from the PV rooftop plant to the use of the average grid mix. Furthermore, the throughput volumes are lower in the *All flex* scenario. In the case of EHP, the unit's annual energy consumption increases due to a shift in demand to times with lower outside temperatures, resulting in lower efficiency. The power supply is less relevant for the ADPm (up to 2.0%). Thus, while the intended structural changes in power supply from flexibilization are apparently beneficial for the GWP of EHP and BEV owners, this is less the case for ADPm impacts and for PVBS in general.
- Impacts resulting from changes in the usage of the generic unit are relevant for PVBS and EHP. Impacts change proportionally with the number of full-load cycles. As for PVBS, impacts are lower in the *All flex* scenario and more relevant for the ADPm (16.0%) than for the GWP (5.9%). Regarding EHP, impacts are higher in the *All flex* scenario and also more relevant for the ADPm (76.5%) than for the GWP (39.6%). Hence, according to our model results, flexibilization is beneficial to the longevity of PVBSs and the connected impacts, but less so for the usage of EHPs.

The comparison of the *All flex* and *No flex* scenarios reveals that non-flexible operation significantly increases the GWP impacts of BEV and EHP units from the perspective of households. In contrast, flexibilization increases GWP impacts in the case of PVBS. Concerning ADPm, non-flexible unit operation leads to lower impacts than flexible operation.

Our results are somewhat in line with and partly contradict the existing literature. Regarding PVBS, Bluhm and Gährs (2023) confirm that external control can significantly increase ADPm impacts due to additional ICT requirements, as well as increased battery usage. However, they find significant GWP benefits instead of disadvantages for flexibilization. Differences can be explained by differences in scope (energy provision for the entire prosumer household with a backward-looking approach to 2018 for different system services), parametrization (access to only 15% of the battery's rated power and parallel PV own-consumption), and methodological choices (an attributional LCA approach based on annual market averages).

Existing LCAs on BEVs also show that optimized charging strategies can significantly reduce GWP impacts per BEV unit (Wohlschlager et al., 2024b; Tang et al., 2021b; Baumann et al., 2019).

Regarding EHPs, we can refer to conceptual considerations (Péan et al., 2019) and manufacturers' statements (Bluhm, 2025), which confirm that flexibilization potentially increases energy consumption and compressor starts, thereby reducing the unit's lifetime and resulting in additional environmental burdens.

3.3. Conflicts and synergies between the system and the household perspectives

Comparing FU I and FU II results reveals that desirable lower GWP impacts occur in both the system and the household perspective of the *All flex* scenario. Furthermore, although environmentally unfavorable, the perspectives are consistent in showing that the ADPm effects are significantly higher in the *All flex* scenario for all three technologies. The divergent GWP and ADPm results again demonstrate a shift in environmental burdens and a transition from a fossil resource-based to a mineral resource-based energy system, from both system and household perspectives.

Moreover, GWP results indicate conflicts for PVBS, as *No flex* impacts are more favorable than *All flex* values for FU II, and somewhat inconclusive results for FU I. However, from these conflicting outcomes, we do not conclude that PVBS owners should remain unaddressed in attempts to flexibilize household technologies. Our results should be viewed in the context of methodological choices: our *w/o PVBS* scenario assumes the availability of alternative flexibility options in the mid-term future. Thus, the importance of externally controlling PVBSs in parallel with dispatchable small-scale and large-scale flexible options diminishes. In contrast, the reverse of what we have modeled applies today: EHPs and BEVs are only just starting to react to external signals, and large-scale flexibility options, such as hydrogen production and reconversion, are in their market entry phase. On the other hand, market players are already pursuing business models based on the deployment of dynamically expanding PVBSs. Furthermore, these players utilize only a portion of the PVBS capacity to protect customers' interests in consuming their own-generated PV electricity and in limiting additional battery usage (Bluhm and Gährs, 2023; Bluhm, 2025). We have assumed full capacity usage instead.

Another conflict might result not from the EHP owners' views regarding the net results of flexibilization but on the increasing technology usage, and thus higher energy consumption. However, since the net GWP results are favorable, we consider this conflict to be a matter of consumer education and financial incentives, which we address below.

3.4. Reflection against the current industry and policy background

Our quantitative modeling results need to be reflected in the context of the current energy economic and energy policy landscape in Germany to put them into practice.

First, our energy system modeling approach assumes nodal dispatch optimization without end-user electricity price components (such as levies, charges, and taxes). In contrast, Germany currently consists of a single market zone with an overarching price signal. Then, several components add to the wholesale market price, resulting in end-customer prices. While a market zone split is a topic of active discussion at the European level with an uncertain outcome (ENTSO-E, 2025), offering dynamic tariffs and variable network charges has become mandatory for energy supply companies as of 2025 (EnWG, 2005; BNetzA, 2023). The new tariff and charges design potentially shifts static consumer behavior towards flexible adaptation to price signals. On the other hand, to our knowledge, current national and federal incentive programs for the purchase of small-scale technologies, among other requirements, necessitate interfaces for external control (e.g., BMWK (2023)). Still, they do not provide for concluding dynamic tariffs or variable network charges. We advocate for assessing whether linking public subsidies to the requirement of external controllability and the conclusion of dynamic energy supply contracts could leverage public expenditures to enable flexibilization.

Second, although the rollout of smart meters, EHPs, and BEVs has been politically specified, the expansion figures are falling short of the targets (BNetzA, 2025b; Roth and Schill, 2025). On the positive side, simplifications and economic relief for the bidirectional charging of PVBSs (also in combination with bidirectional BEV charging points) have been made possible with respective amendments to relevant laws in February 2025 (Solarspitzengesetz, 2025). Pending a decision by the Federal Network Agency (due to be made by June 2026), PVBS owners can store and withdraw grid electricity without losing the PV feed-in tariff. Thus, the law expands the potential uses of storage for innovative business models and products. Furthermore, bidirectional charging for BEVs has not yet been implemented in either technical or regulatory terms. However, initial BEV models with a bidirectional charging option have been launched on the market (Hecht et al., 2023), and energy suppliers expect an economic implementation in their business models by the end of the 2020s, according to our supporting expert interviews (cf. Bluhm (2025)).

Third, stakeholders, including public institutions, consumer protection organizations, technology manufacturers, and energy suppliers, should support customer choices towards flexibilization. They could provide information on the pros and cons of flexibilization, setting sensible default values in energy management systems (Sintov and Schultz, 2017), as well as a tariff design that supports environmentally friendly behavior, e.g., by coupling dynamic prices with additional information about the current renewable energy share as offered by Green Planet Energy (Green Planet Energy, 2025). Consumer activation also requires a careful design of legally mandated incentives. Analyses for Switzerland and Finland demonstrated that PVBS and BEV owners are more willing to provide flexibility and accept potential inconvenience than EHP owners and that consumers prioritize financial gains over environmental gains when opting for demand-response programs, with EHP owners requiring the highest financial compensation (Kubli et al., 2018; Sridhar et al., 2023).

Fourth, flexibilization requires a higher production and use of ICT components. Our analysis has revealed that decreased use and increased recovery of certain materials (gold, silver, and tellurium) could lower ADPm impacts. A comparison of our results to Wohlschlager et al. (2022) (who use the same inventory data for the smart meter infrastructure but a cradle-to-grave system boundary) shows that implementing a European Union-mandated recycling quota of 55% for electronic waste can significantly lower the environmental impacts of the smart meter infrastructure. An increased lifetime, by design, through reparability and second-life strategies, could further reduce impacts. Furthermore, flexibilization potentially increases the use of energy technologies. The production of refrigerants for EHPs is particularly relevant for GWP, EPf, and ODP impacts. Höges et al. (2025) show that the usage of refrigerants such as R436A results in lower impacts. Using alternative cell chemistries and second-life strategies are options for PVBSs and BEVs (Gutsch and Leker, 2022; Philippot et al., 2022). In addition, Gong et al. (2024) demonstrate that bidirectional charging does not necessarily lead to a lower technology lifetime but can even increase longevity, depending on the system service provided and the energy management strategy.

3.5. Limitations

Our results and approach are subject to limitations that may lead to both underestimating and overestimating the potential impacts of the flexibilization of small-scale energy technologies.

In contrast to our cost-optimal dispatch, the users' willingness to allow for external control, as well as additional restrictions by technology manufacturers and operators, limit dispatchability in reality. Furthermore, we did not assess the operators' dispatch strategies or specific use cases (e.g., responses to dynamic tariffs). Therefore, our approach determines environmental potentials under optimal technical and organizational conditions rather than real-life conditions. Additionally, we have neglected user-related effects, such as rebounds, which may offset or enhance environmental savings.

Our scenario definition represents only one possible development pathway of the energy system in the mid-term future. To address this issue and examine, for example, how a slower rollout of BEVs, EHPs, and PVBSs or a delayed phase-out of coal would affect the outcomes, additional scenarios and a comprehensive sensitivity analysis would be required. However, due to the high computational effort associated with such analyses, they could not be conducted within the scope of this study.

On the other hand, alternative neglected effects lead to an underestimation of the environmental potential. Considering reduced grid expansion needs below the 110 kV level would further mitigate impacts in the flexibilization scenarios. Implementing cradle-to-grave rather than cradle-to-gate system boundaries, and considering material recycling or thermal treatment, could both increase (through additional processes and emissions) and decrease (through environmental credits for substitutions) impacts, although these effects would apply symmetrically across all scenarios. In the context of use cases, bidirectional charging of BEVs would enhance the energy system's flexibility. Moreover, accounting for improvements in ICT component production and the technosphere would likely decrease direct effects, leading to higher net savings and lower net burdens, depending on the impact category.

Finally, our generic unit approach for FU II is not representative of actual households because the *eTraGo* time series used here represent aggregates for the entirety of German households. This approach overlooks local demand peaks and results in situations where PVBS charging and discharging coincide, which is unrealistic for individual households.

The generalizability of our results should apply to national energy systems with majority shares of intermittent renewable energies, remaining shares of fossil power plants, increasing degrees of demand-side electrification, and the advancement of digital infrastructure rollout, allowing for modulation of small-scale technologies' energy supply. Less carbon-intensive power plant fleets are less likely to achieve comparable GWP reductions, whereas more carbon-intensive fleets could yield greater reductions. The latter is expected to apply to the German energy system in 2030, given that a certain share of electricity from coal-fired power plants is expected to remain.

The research approach of integrating LCA and energy system modeling could also be applied to studies of other countries. However, careful and substantial changes to the underlying data model would be required to account for country-specific data on energy demands, generation, and economic parameters, as well as their regional distribution and future projections. This also includes a change of life-cycle inventory foreground and background data, such as country-specific ICT component models or suitable Ecoinvent datasets for energy technologies.

4. Conclusion

This article has examined the environmental burdens and benefits of flexibilizing three rapidly scaling energy technologies in households through the installation of additional digital infrastructures, namely BEVs, EHPs, and PVBSs. For this, we proposed a consequential, multi-level life cycle approach that captures the multifaceted, interrelated environmental effects of ICT production and use, small-scale energy technology use, and the macro-scale energy system. Impacts were assessed in eleven impact categories to avoid an unreflected shift of environmental burdens. We applied the approach to Germany's projected mid-term future energy system and analyzed an *All flex* scenario, in which all three small-scale technologies are flexibilized, as well as four scenarios assuming the absence of flexibilization for individual technologies and the entire set of technologies. Unlike the existing literature, this approach enabled examination not only of the significance of the flexibilization of individual technologies, but also of all three, both individually and in combination.

Our results suggest that intensified digitalization for flexibilization is likely to reduce climate change-related emissions in Germany's mid-term future energy system. From the perspective of households, climate change mitigation appears likely for BEVs and EHPs but not for PVBSs. Furthermore, intensified digitalization for flexibilization increases mineral resource depletion, eutrophication, and ozone depletion, resulting from extraction and production processes for ICT components and EHP unit production.

Although the three technologies contribute to environmental impacts to varying degrees, we would not suggest neglecting any of them in flexibilization efforts. EHPs and BEVs have the potential to provide greater flexible capacity in the future, whereas PVBSs are already successfully managed by external providers today. In the future, the relevance of PVBS may decline due to the parallel ramp-up of other small-scale and large-scale flexibility capacities. Crucial to unlocking these potentials is the rapid deployment of digital measurement, communication, and control infrastructure.

From the comparably modest achievable greenhouse gas savings at the national level, we conclude that demand-side flexibilization through intensified digitalization is no silver bullet for reaching the envisaged reduction in greenhouse gas emissions, but it is one viable element in a complementing set of measures. Leveraging 0.8 Mt of greenhouse gas savings, or approximately 8.5% of the remaining emissions gap (conditional on the underlying assumptions), to reach 2030 sector targets represents a significant figure in a future power system already dominated by approximately 80% of renewable energy production. This illustrates that even modest emissions savings are meaningful when alternative low-hanging fruits tend to have already been picked. However, these benefits are accompanied by increased burdens, including mineral resource depletion, freshwater eutrophication, and ozone depletion, primarily from the production and operation of ICT and EHPs. The identified trade-off underscores that digitalization is not environmentally neutral. From the authors' perspective, digitalization is increasingly serving as a coordination mechanism in an increasingly complex energy system (including a large number of controllable energy technologies in households) that is transforming towards climate neutrality, rather than as a stand-alone means of reducing greenhouse gas emissions.

The significance of these findings extends beyond the German context, as demand-side digitalization in the energy sector is promoted by European and global institutions as a means to support (environmentally motivated) energy transition processes. Therefore, technology assessments that capture the multi-layered potential benefits and burdens, as demonstrated in this article, appear all the more relevant for exploring the proclaimed and intended pros and the potentially overlooked cons in a forward-looking, more comprehensive manner.

Unlike large-scale flexibility options such as implementing a hydrogen infrastructure, large-scale battery systems, or grid expansion, the environmental burdens of ICT-enabled small-scale flexibility are distributed across millions of household devices, requiring significant coordination efforts. This calls for a policy approach that simultaneously promotes ICT rollout, mandates circular economy standards for electronic components, and designs financial incentives that reward flexible behavior. Furthermore, digital solution providers should proactively incorporate environmental considerations into their product and tariff design from the outset.

Future research could extend the proposed methodological approach to assess the environmental implications of bidirectional BEV charging and of increasing ICT penetration under alternative energy transition pathways, as these represent the next frontier of digitally enabled flexibility.

CRediT authorship contribution statement

Hannes Bluhm: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Clara Büttner:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ilka Cußmann:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Jonathan Amme:** Validation, Software, Formal analysis, Data curation. **Frauke Wiese:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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.

Appendix A. Additional results

Fig. 4 displays the impact assessment results for FU II with consideration of the life cycle of power plants.

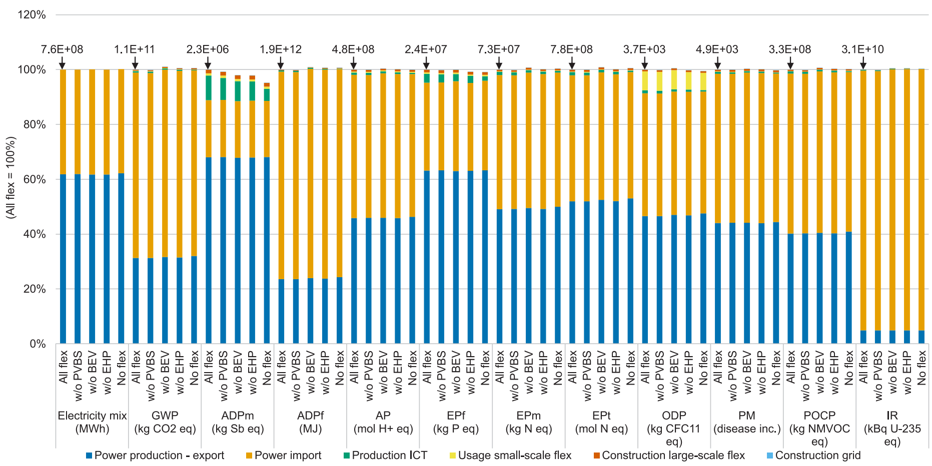

Fig. 4. Impact assessment results for FU I (German power system) including power plant construction.

Appendix B. Life cycle inventory

Table 8 contains detailed information on the life-cycle inventory of digital components. Table 9 specifies the inventories for the energy-related technologies.

Appendix C. Key parameters of the energy system model

See Table 10.

Table 8
Inventory of digital components per unit and used literature sources.

Scenario and location	Item	Amount	Unit	Life-time	Source for type and amount	Source for life-cycle inventory
Non-flexible, per location	Smart meter	1	p	12 a	Wohlschlager et al. (2022), Bluhm and Gährs (2023)	Wohlschlager et al. (2022)
	Smart meter gateway	1	p	12 a	Wohlschlager et al. (2022), Bluhm and Gährs (2023)	Wohlschlager et al. (2022)
	Electricity consumption per smart meter and gateway	17.5	kWh/a	–	Gährs et al. (2021)	*eTraGo*, *eGon2035*
	Data transfer (mix 4G and 5G standards)	0.25	GB/a	–	Wohlschlager et al. (2022)	Bieser et al. (2020)
Flexible, per location (components additional to non-flexible case)	Smart meter	1	p	12 a	Wohlschlager et al. (2022), Bluhm and Gährs (2023)	Wohlschlager et al. (2022)
	Control box	1	p	12 a	Own assumption based on interview	Based on (Wohlschlager et al., 2022)
	Electricity consumption Control box	17.5	kWh/a	–	Own assumption based on (Gährs et al., 2021)	*eTraGo*, *eGon2035*
Flexible, aggregator (attributed to one unit)	Data transfer to aggregator (mix of 4G and 5G standards)	1	GB/a	–	Bluhm and Gährs (2023)	Bieser et al. (2020)
	Data transfer for access to client portal (mix of 4G and 5G standards)	0.2	GB/a	–	Bluhm and Gährs (2023)	Bieser et al. (2020)
	Rackserver	$1.7 * 10^{-3}$	height units	3 a	Bluhm and Gährs (2023)	Gährs et al. (2021)
	Electricity consumption rackserver	2.0	kWh/a	–	Gährs et al. (2021)	*eTraGo*, *eGon2035*
	Laptops	$2.8 * 10^{-4}$	p	3 a	Bluhm and Gährs (2023)	Gährs et al. (2021)
	Electricity consumption laptops	$1.6 * 10^{-2}$	kWh/a	–	Gährs et al. (2021)	*eTraGo*, *eGon2035*

Table 9
Used inventories for energy-related technologies.

Technology	Inventory source	Note (assumed type, Ecoinvent data set used, efficiency adjustment)
Small-scale technologies		
Electrical heat pump	Wernet et al. (2016)	heat production, air–water heat pump 10kW, CH; electricity usagae removed
Battery storage system for PVBS	Wernet et al. (2016)	market for battery, Li-ion, LFP, rechargeable, GLO
Large-scale technologies and grid expansion		
Electrolyzer	Bareiß et al. (2019)	Assumed type: proton-exchange membrane electrolyzer
Fuel cell	Mori et al. (2023)	Assumed type: proton-exchange membrane fuel cell
Hydrogen tank store	Mori et al. (2014)	
Hydrogen cavern store	Raluy and Cortés (2023)	
Methanation	Zhang et al. (2017)	
Steam methane reforming	Wernet et al. (2016)	hydrogen, gaseous, low pressure, steam methane reforming, RER; 0.7319 to 0.74
Large-scale battery systems	Wernet et al. (2016)	market for battery, Li-ion, LFP, rechargeable, GLO
AC and DC lines	Jorge et al. (2012a,b)	Assumed type: AC: 400 kV aerial line, DC: high-voltage DC aerial line

(*continued on next page*)

Table 9 (*continued*).

Technology	Inventory source	Note (assumed type, Ecoinvent data set used, efficiency adjustment)
Power plants		
Oil	Wernet et al. (2016)	electricity production, oil, DE; 0.3947 to 0.43
Others	Wernet et al. (2016)	electricity production, oil, DE; 0.373 to 0.35
Reservoir	Wernet et al. (2016)	electricity production, hydro, reservoir, non-alpine region, DE
Run-of-river	Wernet et al. (2016)	electricity production, hydro, run-of-river, DE
Solar	Wernet et al. (2016)	electricity production, photovoltaic, 570 kWp open ground installation, multi-Si, DE
Solar roof-top	Wernet et al. (2016)	electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted, DE
Wind offshore	Wernet et al. (2016)	electricity production, wind, 1-3MW turbine, offshore, DE
Wind onshore	Wernet et al. (2016)	electricity production, wind, >3MW turbine, onshore, DE
Biomass	Wernet et al. (2016)	heat and power co-generation, wood chips, 6667 kW; 0.3947 to 0.47
Central biomass CHP, industrial biomass CHP	Wernet et al. (2016)	heat and power co-generation, wood chips, 6667 kW; 0.3947 to 0.43
OCGT	Wernet et al. (2016)	electricity production, natural gas, conventional power plant, DE; 0.3803 to 0.42
Central gas CHP	Wernet et al. (2016)	heat and power co-generation, natural gas, conventional power plant, 100 MW electrical, DE; 0.4364 to 0.43
Industrial gas CHP	Wernet et al. (2016)	heat and power co-generation, natural gas, conventional power plant, 100 MW electrical, DE; 0.4364 to 0.43
Hard coal	Wernet et al. (2016)	electricity production, hard coal, DE; 0.3205 to 0.33
Nuclear	Wernet et al. (2016)	electricity production, nuclear, pressure water reactor, DE

Table 10
Exogenously defined electricity generation capacities and energy demands in Germany in the used energy system model based on Büttner et al. (2024).

Parameter	Value	Unit	source
Gas generation capacity	46.7	GW	German TSOs (2021)
Oil generation capacity	1.3	GW	German TSOs (2021)
Pumped hydro generation capacity	10.2	GW	German TSOs (2021)
Wind onshore generation capacity	90.9	GW	German TSOs (2021)
Wind offshore generation capacity	34.0	GW	German TSOs (2021)
Solar generation capacity	120.1	GW	German TSOs (2021)
Biomass generation capacity	8.7	GW	German TSOs (2021)
Other generation capacity	5.1	GW	German TSOs (2021)
Electricity demand residential	115.1	TWh_{el}	German TSOs (2021)
Electricity demand commercial, trade, and service	123.5	TWh_{el}	German TSOs (2021)
Electricity demand industry	259.5	TWh_{el}	German TSOs (2021)
Heat demand residential	379.0	TWh_{th}	[a]
Heat demand commercial, trade, and service	122.0	TWh_{th}	[a]
CH_4 demand industry	196.0	TWh_{CH_4}	Guminski et al. (2021)
H_2 demand industry	16.1	TWh_{H_2}	Guminski et al. (2021)
H_2 demand transport	26.5	TWh_{H_2}	[a]
Motorized individual travel demand transport	41.4	TWh_{el}	[a]

[a] Own calculation.

Data availability

This work follows open source and open data principles. For this, we provide two repositories:

• The result data is available via *Zenodo*: https://doi.org/10.5281/zenodo.17311213

• The tool eTraGo with a dedicated branch for the underlying model for this article is published on *GitHub*: https://github.com/openego/eTraGo/tree/0dfc0d01e494b2c5cca87aa9cfcf8606564b2841.

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