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Towards a Holistic Life Cycle Assessment of Emerging Technologies in Future Energy Systems – Insights on Smart Charging

Daniela Wohlschlager, M.Sc.

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Vorsitz: Prof. Dr.-Ing. Matthias Gaderer

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1. Prof. Dr. Magnus Fröhling
2. apl. Prof. Dr. Patrick Jochem

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Abstract

The transition towards climate neutrality necessitates a fundamental shift from centralized, fossil-based energy systems to increasingly decentralized systems powered by renewable energies (RE). The literature highlights the need for sector-integrated thinking through the shift to Smart Energy Systems (SES) to efficiently integrate RE. This is accompanied by increasing electrification. One key example of electrification is the switch to battery electric vehicles (BEVs). Concurrently, information and communication technology (ICT) facilitates various cross-sectoral applications for coordinating volatile, decentralized production and increasing loads from changing consumption patterns. This includes use cases for providing flexibility to the energy system, e.g., by controlling decentralized consumers, producers, or storage options.

The positive impacts of ICT-enabled use cases to decrease combustion-based emissions in energy systems are well researched. Integrating digitalization, however, can yield adverse environmental impacts alongside the intended benefits. This includes impacts from the resource and energy use of required ICT components. These effects of ‘first-order’ can be identified through the standardized Life Cycle Assessment (LCA) method. However, a diffusion of novel use cases involves systemic repercussions and complex interactions between technologies and the energy system. Quantifying such effects of ‘higher-order’ requires additional approaches beyond an LCA, as technological developments and implications within the energy system need to be considered consistently.

As a methodological contribution, this dissertation outlines a conceptual framework to assess the environmental effects of use cases in SES and consolidates approaches for quantification. Established methods allow LCA professionals to include broader perspectives when evaluating the impact of use cases in SES, reaching from the technology to the system level. Combining a prospective Life Cycle Assessment (pLCA) with energy system modeling allows for addressing these first- and higher-order effects. Provided methods facilitate the quantification of medium- and long-term impacts. Researchers dealing with environmental impacts in future energy systems can build upon the conceptual framework and methodological approaches.

Validated through an exemplary model study, this work further provides quantitative insights into the environmental implications of smart charging. When using BEVs as flexibility options through Vehicle-to-Grid (V2G) charging, results show an accelerated integration of RE and lower emissions of electricity generation in the medium-term. This further affects the impacts at the technology level, reducing the environmental amortization time (‘break-even’) of BEVs with ICEVs. While price-optimized V2G charging causes significant repercussions on local distribution grids, the analysis concludes that a balance of various charging use cases can decrease the systemic environmental consequences. By identifying the potential implications of climate change, findings of this prospective assessment can guide policy and industry towards a sustainable integration of BEVs. When implemented strategically, charging strategies can serve as an enabling technology to accelerate the transition toward climate-neutral SES.

Acknowledgments

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Sometimes, you must walk your individual path, trust in the process, and have a healthy dose of optimism to believe everything will eventually fall into place. Along this journey of my Doctoral Degree, I luckily met many people who kept me going. First, I want to thank Prof. Wolfgang Mauch and Prof. Ulrich Wagner, who inspired and motivated me to start this journey. As I navigated through the hills and valleys, I found immense support in the incredible team at FfE, particularly the ‘Öko-Team’ under the guidance of my mentor Anika Neitz-Regett, and the ‘unIT-e^2’ project team with the ever-supportive lead by the Elisabeth Springmann, Adrian Ostermann, and Simon Köppl. Furthermore, I am more than happy that my path was guided under the comprehensive supervision of Prof. Magnus Fröhling – many thanks for your generous investment of time and knowledge.

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Abbreviations

BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
ESM	Energy System Model
EVSE	Electric Vehicle Supply Equipment
FU	Functional Unit
GHG	Greenhouse gas
GWP	Global Warming Potential
IAM	Integrated Assessment Model
ICEV	Internal Combustion Engine Vehicle
ICT	Information and Communication technology
iMSys	Intelligent Metering Systems
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OEM	Original Equipment Manufacturer
pLCA	Prospective Life Cycle Assessment
pLCI	Prospective Life Cycle Inventory
PV	Photovoltaic
RE	Renewable Energies
RQ	Research Question
SES	Smart Energy System
SoC	State of Charge
V1G	Unidirectional controlled charging
V2G	Vehicle-to-Grid (Bidirectional)
V2H	Vehicle-to-Home (Bidirectional)
V2X	Vehicle-to-X (Bidirectional)

1 Introduction

1.1 Motivation: Transformation into Smart Energy Systems (SES)

The path toward climate neutrality requires substantial changes to traditional energy systems. In contrast to most European countries that aim for climate neutrality by 2050, Germany set this goal for 2045 (German Federal Ministry for Economic Affairs and Climate Action, 2023). One cornerstone is the expansion of renewable energies (RE), fostered by the German Renewable Energy Sources Act (EEG). By 2023, national electricity generation from RE covered 51.8% of Germany's consumption (UBA, 2024b). After wind energy (>50%), photovoltaic (PV) systems provided 22.5% of RE generation. More than two-thirds of added PV capacities in 2023 are subsidized via the feed-in tariff of EEG (UBA, 2024b), i.e., installed on a smaller scale, including rooftop and open space installations. This shows the shift from centralized, large-scale production (e.g., nuclear or coal power plants) in traditional energy systems to decentralized generation from volatile RE. In contrast to the comparatively high RE share within electricity generation, RE only covered 22% of Germany's total gross final energy consumption by 2023 (UBA, 2024b). Reaching the climate targets, however, necessitates transforming the entire energy system. This requires using electricity from RE across different sectors, e.g., through energy conversion or electrification (Lund et al., 2017).

One of the critical sectors that face increased electrification is transportation. Among all sectors, transportation currently has the lowest RE share, with 7.3% (UBA, 2024b). While Germany reached an overall reduction of greenhouse gas (GHG) emissions by 40% from 1990 to 2022, the transport sector has reached the lowest reduction with a decrease of just 9.1% (UBA, 2024a). Moreover, transportation emitted 20% of national GHG emissions, i.e., 147 $MtCO_2e$, whereas motorized passenger cars contribute approx. 60% (Koller et al., 2024). Besides efforts towards a more sustainable modal split, policymakers recognize the switch from conventional internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs) or fuel-cell electric drive vehicles as a vital element to reach climate neutrality. According to EU legislation, new registrations of CO_2-emitting cars are to be phased out by 2035 (European Parliament, 2023). Next to plug-in hybrid cars, which currently amount to 2.9 million vehicles in Germany, the share of BEVs has increased over the last few years. From 2023 to 2024 alone, the number of BEVs increased by 39%, reaching 1.4 million, and thus, a share of 2.9% of Germany's passenger car fleet (49 million) (KBA, 2024). By 2030, the government aims to reach 15 million BEVs (BMDV, 2023). The example of the transport sector shows the magnitude of additional consumers entering the electricity system through increased electrification. As the share of fluctuating electricity production rises and consumption patterns change, the complexity of managing generation and supply increases.

As an enabler for the energy transition, EU policymakers have regarded implementing information and communication technologies (ICT). In Germany, the Act on the Digitalization of the Energy Transition, as relaunched in May 2023, aims to improve electricity supply, grid operation, and planning through data on generation, consumption, and grid status. The law stipulates accelerating the rollout of ‘smart meters,’ i.e., as part of the intelligent metering infrastructure (iMSys), and the introduction of dynamic electricity tariffs as planned by 2025 (Federal Government of Germany, 2023). Using ICT for real-time monitoring and control of generation and supply, literature often refers to the transformation into a ‘smart grid’ (Hassan et al., 2024; Kabeyi & Olanrewaju, 2023). A review by Lund et al. (2017) concludes that while most definitions of smart grids focus on solutions for the electricity system only, the necessary cross-sectoral transformation requires a ‘smart energy system’ (SES) instead. According to the definition, an SES encompasses three types of smart grids, i.e., smart electricity, thermal, and gas grids. Combined with storage technologies, these are coordinated to identify synergies for optimal solutions for individual energy sectors and the overall system (Lund et al., 2017). The authors further highlight the need for new flexibility forms to deal with the volatile supply from RE. Concluding from a review, Degefa et al. (2021, pp. 2–3) define flexibility options as having the ability “*to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions.*” Smart electricity grids' flexibility options include connecting volatile RE production with flexible electrical consumers, e.g., BEVs and heat pumps. Flexibility of smart thermal and gas grids includes the conversion of electricity for district heating or the conversion into hydrogen (Lund et al., 2017).

With flexibility provision being one example, ICT enables novel use cases for energy systems. In this context, Ostermann et al. (2023) define a ‘use case’ as a description of the system’s functionality from a user's perspective, which can be an individual, a role, an organization, or another system. Similarly, a review by Weigel and Fischedick (2019) categorizes use cases in the energy sector into applications from the actor's point of view, including system balancing, process optimization, and customer-oriented use cases. To allow cross-sectoral use cases in SES, ICT is required among the system’s actors of the energy system (see Figure 1).

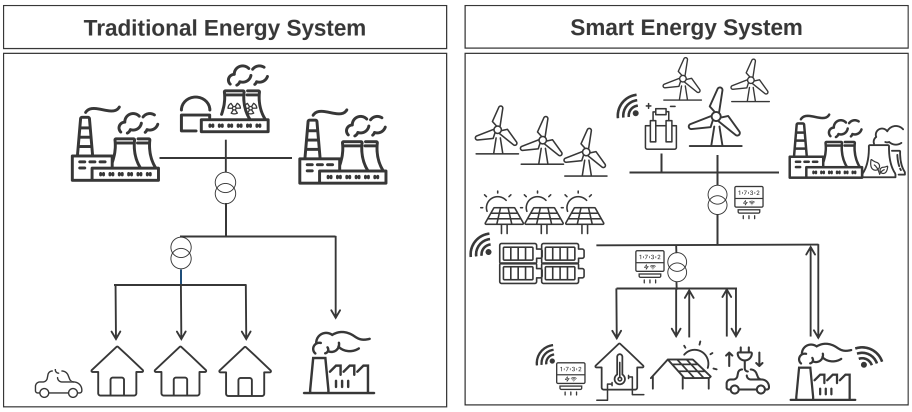

Figure 1: Shift from Traditional Energy Systems to Smart Energy Systems

1.2 Related Work: Environmental Impact Assessment of Use Cases in SES

While designed to enhance system efficiency and sustainability, the large-scale implementation of ICT-enabled use cases can yield adverse environmental impacts, e.g., caused by the energy and resource use of additional power electronics. The environmental effects of ICT have been widely discussed in the research field ‘ICT for Sustainability’ (ICT4S). Defined by Hilty and Aebischer (2015), the aims of ICT4S are two-fold: reducing energy and material flows of ICT from a lifecycle perspective (i.e., sustainability in ICT) and enabling sustainable production and consumption (i.e., sustainability by ICT). Previous frameworks on the environmental effects of ICT (see review by Pohl et al. (2019)) identified direct effects of ’first-order’ and indirect effects of ’higher-order.’ By definition, the effects of first-order results from the lifecycle impact of ICT hardware and can be evaluated through the standardized Life Cycle Assessment (LCA) method. As defined in DIN EN ISO 14040, 2006, an LCA allows to account for all impacts along the lifecycle stages of a product or service, from raw material extraction to end-of-life treatment. On the other hand, higher-order effects include both intended benefits and unintended side effects that occur beyond the technology level of ICT (Coroamă et al., 2020). Pohl et al. (2019) outline higher-order effects on the ‘technology,’ ‘user,’ and ‘system’ levels. Effects on the user level involve changes in user behavior. Effects on the system level include repercussions of large-scale diffusion on the overall system in which the technology operates.

As outlined in Wohlschlager et al. (2023), considering the effects of higher-order when assessing ICT, specifically in SES, increases the complexity and requires an enhancement of the standardized LCA method. First, including higher-order effects involves an expansion of the system boundaries and considering interactions between effects on different levels. One approach to determining higher-order effects of novel use cases is scenario modeling. Researchers typically apply an energy system model (ESM) to plan future energy systems. ESMs have generally focused on minimizing or constraining direct CO_2 emissions from fossil fuel combustion when assessing environmental impacts. With the shift towards RE-based systems, the significance of impacts occurring along the lifecycle, including manufacturing processes, has escalated (Addanki et al., 2024). Combining an LCA with the approach of energy-scenario modeling to determine the lifecycle impacts of a specific energy transition has been recognized as one form of an LCA, i.e., an integrated LCA (Guinée et al., 2018). As summarized in Wohlschlager et al. (2024), methodological developments in combining these two approaches have been continuously developed.

These approaches, however, face difficulties in considering the changing impacts caused by future developments. This challenge also occurs when assessing the impact of use cases in SES, which are currently in an early stage of market penetration. While the standardized LCA is commonly applied to investigate the impact of established technologies, a prospective Life Cycle Assessment (pLCA) evaluates the potential impacts of emerging technologies at a future time (Arvidsson et al., 2018). As outlined in Steubing et al. (2023), a pLCA emphasizes the importance of aligning the technology under study (foreground system) with the expected system it will operate in (background system). According to the authors, this requires considering medium- to long-term scenarios where the global economy, society, and environment may differ from today. Research on pLCA still needs enhancement to ensure comparability and accurate data gathering. Challenges occur since the process must also account for uncertainties (Thonemann et al., 2020) and confront the absence of standardized methodologies within this domain (Fröhling & Hiete, 2020).

As we embrace new ICT-enabled applications within SES at an early market penetration stage, potential impacts must be determined before a large-scale penetration. This is crucial to avoid investments leading to energy-intensive path dependencies and guide policymakers toward sustainable systems in the long run (Fouquet, 2016). Besides impacts on the technology level, e.g., from ICT infrastructures, this includes impacts of higher-order such as repercussions within the overall energy system. Due to the abovementioned challenges, researchers require methodological guidance on quantifying these impacts.

1.3 Goals and Research Questions

While the technical options of using ICT in the energy sector are well researched (see review by Weigel and Fischedick (2019)), determining associated environmental impacts in the medium and long-term exceeds the capability of the standardized LCA method. The overall goal of this dissertation is to methodologically enhance the lifecycle-based assessment of future energy systems by incorporating repercussions caused by emerging technologies. Applied to exemplarily assess use cases in SES, the dissertation aims to provide quantitative insights on the magnitude of effects on different levels and the main levers for minimizing the impacts. By doing so, this dissertation enables researchers to evaluate and draw conclusions for industry and policymakers on the role of novel use cases in reaching climate-neutral energy systems. To achieve these goals, this work follows two overarching research questions (RQ).

First, this dissertation develops a conceptual framework and methodological approaches for a holistic impact assessment by answering the following question:

RQ 1: How can the prospective lifecycle-based environmental effects of emerging use cases in Smart Energy Systems be evaluated?

Secondly, this dissertation proves the feasibility of the approaches resulting from RQ 1 through an exemplary application to specific use cases within SES. Researchers often apply such a model study of one or more use cases (cf. Schmidt (2021)) to demonstrate the feasibility of developed methods and tools. As an exemplary application, the dissertation assesses the charging strategies of BEVs. Sovacool et al. (2017) outline the umbrella term 'Vehicle-Grid-Integration,' which encompasses concepts for integrating electromobility into the energy system. According to a recent review by Baumgartner et al. (2023), synonyms appearing in literature are ‘controlled,’ ‘intelligent,’ or ‘smart charging,’ which further distinguish between ‘unidirectional’ and ‘bidirectional’ charging. Huber et al. (2019, p. 2) define smart charging as *‘an information system that optimizes the charging process towards one or multiple objectives besides reaching a desired state of charge (SoC)*[1] *within a given time frame.’* Besides unidirectional controlled charging (V1G), i.e., a one-way flow of electricity to the vehicle, bidirectional charging of BEVs further allows electricity discharge. Kempton and Letendre (1997)introduced the concept as *‘a two-way, computer-controlled connection to the electric grid. That is, the grid could receive power from the vehicle and provide power to the vehicle.’* Ever since, a broad range of applications for different purposes have been developed, generically referred to as Vehicle-to-X (V2X). As outlined in a review by Pearre and Ribberink (2019), the established terminologies for different use cases depend on the external entity to which the electricity is returned. Supplying electricity to the grid is referred to as Vehicle-to-Grid (V2G). The utilization of discharged electricity in a residential or commercial setting is known as Vehicle-to-Home (V2H) and Vehicle-to-Building (V2B). There are several use cases of charging strategies, depending on the purpose (Pearre & Ribberink, 2019). For the example of V2G, use cases include services for grid operators, e.g., frequency regulation. From an end-user perspective, use cases such as energy arbitrage offer revenue potentials by minimizing the operational costs of BEVs. Figure 2 illustrates the changing load curve of a household for the example of V2H, i.e., controlled charging in combination with a PV system. As outlined, unidirectional charging can shift the hours of charging to times of high RE availability. Bidirectional charging further allows electricity discharge, e.g., to increase self-consumption or to decrease peak loads.

The choice of investigating the charging strategies of BEVs as exemplary use cases in this dissertation has been made for several reasons. Firstly, the electrification of passenger transport in Germany has been legally decided. The expected large-scale diffusion demands ICT to efficiently integrate BEVs into existing energy infrastructures. Secondly, charging strategies allow BEVs to fulfill multiple purposes. While BEVs switch from a load to the role of a controllable consumer in the case of unidirectional charging, bidirectional charging further enables the secondary function as a storage unit. BEVs thus represent a flexibility option. Exemplarily investigating charging strategies, including bidirectional charging, is a strategic choice. Once the developed frameworks and methods are validated with this example, a transfer is highly feasible to assess similar use cases in SES, specifically those classified by Weigel and Fischedick (2019) as part of ‘smart market & flexibility integration’ for system balancing. This includes the intelligent control of decentralized producers (e.g., PV systems), consumers (e.g., BEVs, heat pumps), or storage units (e.g., batteries).

[1] The State of Charge (SoC) describes the available battery capacity expressed as a percentage of its total capacity.

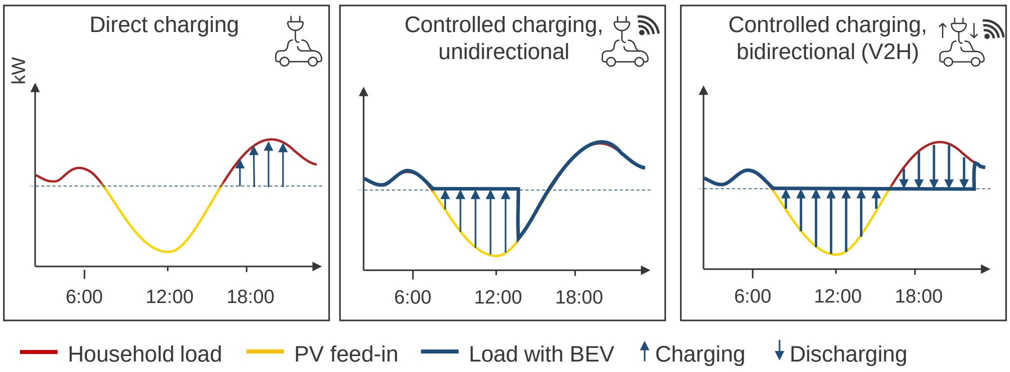

Figure 2: Changing load curve depending on the charging strategy

Besides validating the developed methods, the exemplary application enhances the insights into the lifecycle impact of different charging strategies. While previous impact assessments of charging strategies primarily focus on single effects, this work includes approaches to assess the effects of first- and higher-order. The prospective approach allows for determining the potential systemic impacts of charging strategies before a large-scale integration. With a focus on assessing the contribution to climate-neutral SES, this dissertation primarily investigates the impact category of climate change within the model study. The resulting second RQ is:

RQ 2: When applied to assess charging strategies of battery electric vehicles, what are the prospective positive and negative effects on climate change resulting from a large-scale penetration?

Figure 3 illustrates the two overarching questions of this dissertation, i.e., focusing on method development (RQ 1) and a model study to assess the charging strategies of BEVs (RQ 2).

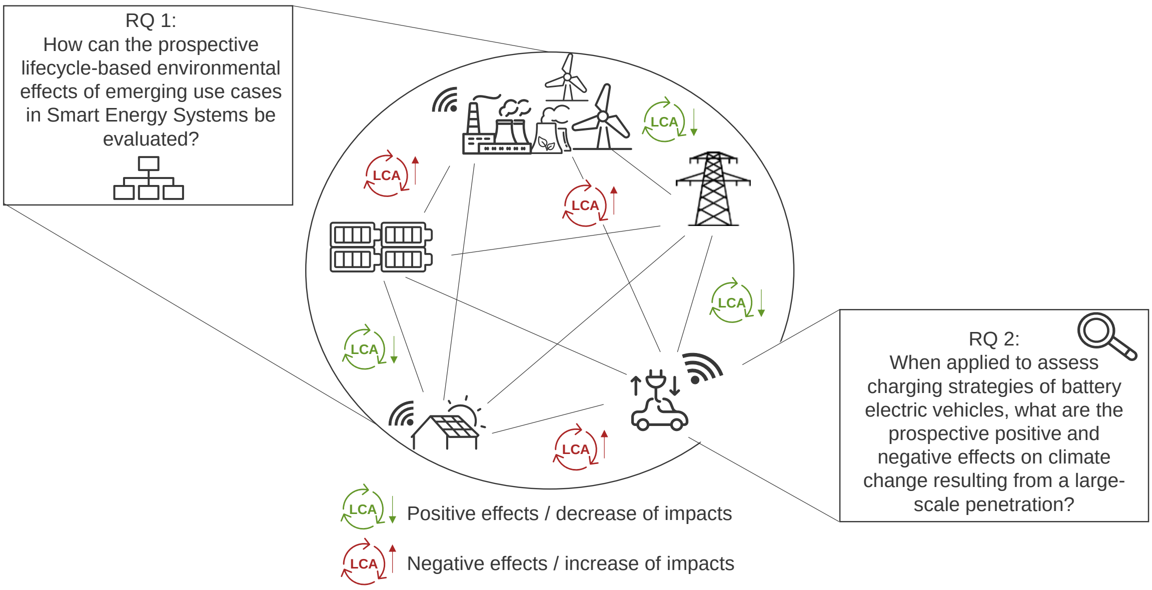

Figure 3: Illustration of the two overarching RQs of this dissertation

1.4 Research Objectives

Table 1 summarizes the three main research objectives and their contribution to answering the RQs. In detail, these objectives are as follows:

<u>Assessing environmental effects of SES:</u> As summarized in Wohlschlager et al. (2023), the literature reports challenges during the environmental impact assessment of use cases in SES. Examples are LCA studies on virtual PV battery storage (Gährs et al., 2021), residential smart home energy management (Pohl et al., 2021), or use cases of intelligent energy metering (Wohlschlager et al., 2021; Wohlschlager et al., 2020). Accordingly, initial difficulties arise during the orientation phase of an LCA before the actual analysis, where professionals have to identify the research question and relevant stakeholders. The goal and scope phase also presents obstacles, such as defining the functional unit (FU) and system boundaries. A critical issue when collecting Life Cycle Inventory (LCI) data for assessing ICT is insufficient access or outdated data, leading to overly narrow system boundaries (Arushanyan et al., 2014). While limited data access represents a common challenge of LCAs, data collection is especially challenging when addressing higher-order effects, such as repercussions on the overall energy system. Additional challenges are related to the emerging character of use cases in SES. This involves the problem of having immature product systems and deployments depending on future decisions in a changing, dynamic technical context (Miller & Keoleian, 2015). By now, the literature lacks a detailed analysis of challenges for assessing the effects in SES of first- and higher-order and potential strategies for addressing them.

The resulting *research objective No. 1 on assessing the environmental effects of SES* aims to derive a conceptual framework for dealing with the effects of first- and higher-order, associated explicitly with use cases in SES. This includes identifying challenges for an LCA-based assessment of relevant effects and providing orientation strategies to address these. Results serve as the starting point for the method development for quantification, which is subsequently applied to assess the charging strategies of BEVs in the following research objectives:

<u>Determining impacts on the technology level:</u> In the case of charging strategies of BEVs, electric vehicle supply equipment (EVSE) represents the required ICT responsible for the effects of first-order on the technology level. As summarized in Wohlschlager et al. (2022), the required ICT in Germany constitutes charging equipment such as a wallbox and intelligent (‘smart’) metering infrastructure (iMSys). The use phase further depends on the national electricity mix during the operating hours of the infrastructure, i.e., the charging profile of the user. The required ICT components and the use phase thus depend on the charging strategy (e.g., V2X compared to unidirectional or uncontrolled charging). Existing LCA studies are limited to the assessment of specific hardware devices (e.g., Bekel and Pauliuk (2019)) or geographical areas other than Germany (e.g., Zhang et al. (2019)) and exclude a prospective approach for the LCA.

Research objective No. 2 on determining impacts on the technology level aims to assess the differing impact of the required ICT for EVSE depending on the charging strategy today and in future scenarios. This involves developing a method for setting up a pLCA and closing data gaps regarding the LCI of components and measurements for data transmission. Applying the method to charging strategies provides insights into the effects on the technology level now and in the future, revealing major levers for reducing the impacts.

Determining impacts on the system level: As stated in a review by Pohl et al. (2019), higher-order effects of ICT involve systemic effects resulting from the large-scale adoption of the investigated product or service. In energy systems, such systemic repercussions are typically determined through an ESM. As summarized in Wohlschlager et al. (2024), methodological approaches for combining LCA and energy system modeling have evolved, including studies explicitly assessing charging strategies. For instance, Arvesen et al. (2021) focus on unidirectional charging while excluding bidirectional use cases. Xu et al. (2020) investigate systemic effects on European electricity production of V1G and V2G but do not consider a consistent pLCA approach. However, a large-scale penetration of novel use cases causes repercussions in future energy systems. Consequences on the system level include changing GHG intensities of electricity, which affect the impact of BEVs as a higher-order effect on the technology level. The electricity mix in hours of charging and, in the case of V2X, discharging is decisive for the operational impact of BEVs (Buberger et al., 2022; Hirz & Nguyen, 2022). An impact assessment thus requires electricity emission factors to be in an hourly resolution. Naumann et al. (2024) highlight the relevance of an hourly resolution since the integration of RE causes high fluctuations of emission factors throughout the day. Reviewed studies on the impacts of smart charging insufficiently investigate how a large-scale penetration of charging strategies affects hourly electricity generation and, subsequently, the technologies' impact (e.g., operation of BEVs). Another systemic consequence concerns the repercussions of novel use cases on grid infrastructures. For example, Gemassmer et al. (2021) and Müller et al. (2022) explore charging strategies in Germany. Besides the contribution to balance RE integration and BEV consumption, the authors outline that V2G charging can cause significant grid reinforcement requirements in low-voltage levels. An environmental assessment of such, however, is excluded in previous studies.

To close the identified research gaps, *research objective No. 3 on impacts on determining impacts on the system level* aims to assess systemic repercussions within energy systems and their consequences on impacts on the technology level. The method development involves the combination of the approaches of a pLCA and scenario modeling using ESMs. Applied to a comparative impact assessment of charging strategies, the aim is to outline systemic effects and their consideration to determine BEVs' footprint.

Table 1: Identified research gaps and resulting research objectives per RQ

No.	Literature Gaps	Research Objectives	Contribution to RQ RQ 1: Methods	 RQ 2: Application
1	LCA-based investigations of use cases in SES faced challenges. It lacks a comprehensive overview of obstacles along the phases of an LCA and respective solution approaches for an assessment.	Outlining potential environmental effects associated with use cases, specifically in SES. Providing orientation strategies and recommendations to guide LCA professionals toward a holistic environmental assessment.	✓ (environmental effects and orientation strategies for assessment)	
2	Studies on the first-order effects of ICT in SES are limited. A comparison of the ICT required for EVSE of a specific use case, including hardware components, data processing, and respective LCI data, must be included.	Providing a pLCA framework and filling data gaps through empirically collected data on required ICT for EVSE, including hardware and data processing. Applying a model study to derive conclusions on the role of charging strategies for climate-neutral SES.	✓ (approaches to assess the technology level)	✓ (ICT for EVSE)
3	Impact assessments of use cases in SES require investigating prospective impacts of higher-order resulting from a large-scale diffusion. Also, the interplay between systemic effects and the consequences of the technologies' impact must be considered.	Providing a methodological set-up to determine the prospective impact of novel use cases due to repercussions within future energy systems. Applying a model study to derive conclusions on the role of charging strategies for climate-neutral SES.	✓ (approaches to assess the system level)	✓ (electricity generation, distribution grid infra-structures)

1.5 Dissertation Outline

To elaborate upon the two overall RQs and research objectives of Table 1, this dissertation is structured in three main parts: a conceptual framework, the method development, and the application of these methods on a model study for charging strategies (see Figure 4).

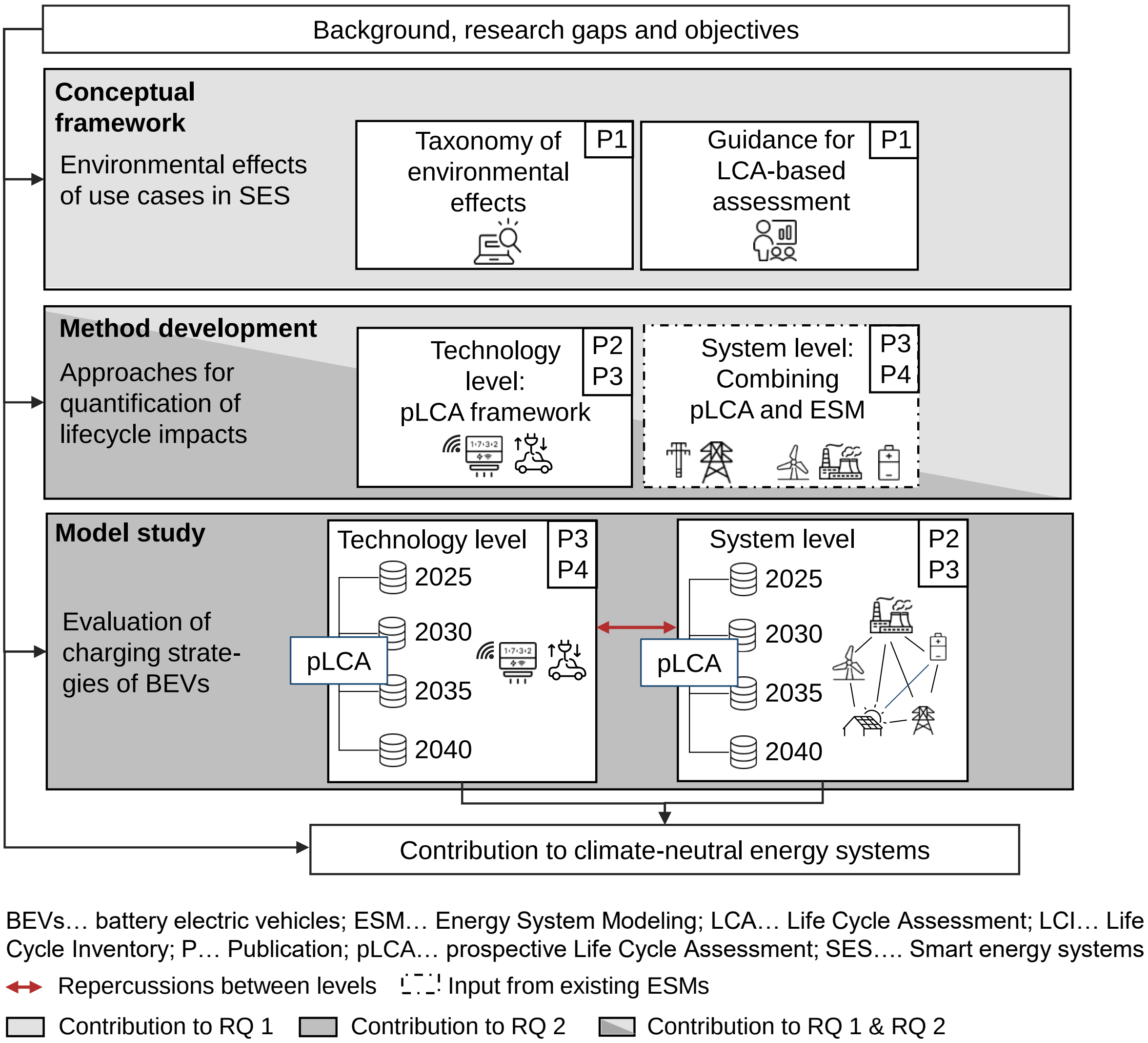

Figure 4: Structure of the dissertation and contribution per publication

Developing the conceptual framework of environmental effects in SES contributes to answering RQ 1. While the outlined approaches focus on the exemplary model study of charging strategies, the methodological steps can be transferred to assess other use cases in SES. The part of method development thus contributes to both RQs. Finally, the model study provides insights into the prospective positive and negative environmental effects of large-scale penetration of charging strategies, as requested in RQ 2.

In detail, these three parts are conducted as follows:

Part I – Conceptual framework: First, literature on the potential environmental effects of ICT in general is investigated. By clustering and comparing determined effects in literature, this dissertation establishes a novel taxonomy of effects relevant to use cases in SES. Challenges for quantifying these effects are consolidated through a meta-analysis of existing studies and a reflection with experts. This serves as the basis for generating a set of corresponding solution approaches. The developed conceptual framework categorizes the most severe effects and recommendations for LCA professionals to address these.

Part II – Method development: While the conceptual framework serves as the fundamental basis of environmental effects in SES, the second part of this dissertation develops methods to quantify the associated lifecycle-based impacts. The focus is on methods for assessing the effects on the technology and system levels, which are applied in the subsequent model study on charging strategies (Part III). The methodological approach of an LCA, as defined in the ISO norms 14040:2021/14044:2006, serves as a starting point. The standardized LCA includes four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Since the conceptual framework identifies the standardized LCA method as insufficient for assessing use cases in SES, the approach is expanded and supplemented with additional methods. This encompasses a future-oriented (prospective) approach, i.e., a pLCA, as SES represent emerging systems. To evaluate systemic effects within the energy system resulting from a large-scale penetration, the pLCA is further combined with scenario modeling using an ESM. While the resulting method can be transferred to assess other impact categories, this dissertation focuses on 'climate change' to determine the role of use cases in SES in reaching climate neutrality. Measured in kg CO_2-equivalents (CO_2e), all relevant GHG emissions along the lifecycle stages are considered. The '100-year Global Warming Potential' (GWP100a) is used for the evaluation, i.e., measuring the impacts of released emissions over 100 years.

Part III – Model study: Lastly, the developed methodological approaches are applied to quantify the prospective effects of charging strategies. The model study compares charging strategies of BEVs, including use cases of uni- and bidirectional charging compared to uncontrolled charging. This exemplary application fulfills two purposes, i.e., the feasibility proof of the developed methods and providing quantitative insights on the effects of charging strategies. This dissertation further reflects on the relevance of considering systemic effects when assessing the technology level. Therefore, the resulting systemic repercussions are considered to determine the operational emissions of BEVs and the environmental performance compared to ICEVs. The model study compares the magnitude of identified effects on different levels by outlining the respective annual impacts for the FU operating one BEV per year.

As displayed in Figure 4, this cumulative dissertation is compiled in four key publications (P1 – P4). Section A1 of the Annex provides an overview of the publications. The conceptual framework (Part I) is established and presented in Publication 1 (see Section 2). The steps of the developed methods (Part II), along with the resulting impacts on climate change for use cases of charging strategies (Part III), are presented in Publication 2 for the technology level (see Section 3.1), as well as Publications 3 and 4 for the system level (see Sections 3.2 and 3.3). Sections 2 and 3 summarize this dissertation's research aims, methodological approaches, results, limitations, and contributions as compiled within these four key publications.

2 Environmental Effects of Use Cases in SES

The starting points of this dissertation are methodological issues that occurred in previous LCA-based evaluations of SES. As novel use cases emerge at the interface between digitalization and energy systems, literature reports diverse intended and unintended environmental effects. In this context, the standardized LCA method has been identified as insufficient for an evaluation. Contributing to the conceptual framework of this dissertation (Part I, see Section 1.5), the Publication 1[2] deals with the need for methodological guidelines to reach a holistic impact assessment. The following investigation thus represents the first step for answering RQ 1, i.e., on how to evaluate the environmental effects of emerging use cases in SES.

Research Aims

To develop a conceptual framework as part of research objective No. 1 (see Table 1), the first aim is to identify potential environmental effects related to use cases in SES. For each effect, the study aims to consolidate reported methodological issues in previous LCA-based assessments and to provide respective solution approaches. As a result of the literature outlined in Publication 1, challenges specifically occur during the methodological set-up of the LCA. Solution approaches are therefore aimed at the following matters:

- setting up the playing field of the LCA
- defining the goal and scope elements
- collecting data for the life cycle inventory phase and addressing missing data
- considering future developments of the technical systems involved

Methodological Approach

Built upon the existing body of literature on impact assessments of ICT, a review of reported environmental effects serves to develop the conceptual framework of this dissertation. By reflecting on the general impacts of ICT in the context of energy systems, the effects are translated into impacts relevant to use cases in SES. Next, methodological challenges to assess these effects are consolidated to establish solutions. For this step, two approaches are combined. First, seven thematically relevant research projects are systematically examined on faced

[2] Wohlschlager, D., Bluhm, H., Beucker, S., Pohl, J., & Fröhling, M. (2023). Overcoming challenges in life cycle assessment of smart energy systems – A map of solution approaches. Journal of Cleaner Production, 423, 138584. https://doi.org/10.1016/j.jclepro.2023.138584

CRediT authorship contribution statement: Wohlschlager, D.: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. Bluhm, H.: Conceptualization, Methodology, Investigation, Resources, Visualization, Funding acquisition, Writing – original draft, Writing – review & editing. Beucker, S.: Investigation, Resources, Writing – original draft, Writing – review & editing. Pohl, J.: Investigation, Resources, Writing – original draft, Writing – review & editing. Fröhling, M.: Writing – review & editing, Supervision challenges and reported recommendations for overcoming these. The central criterion for the case selection is the thematic orientation rather than representativeness (Etikan, 2016). For comparability, the choice is on use cases specifically applied by small-scale consumers in SES (e.g., households). The geographical scope is Germany. Secondly, the findings from this systematic examination of research projects are further enhanced through a reflection with LCA professionals from research, consulting, and industry. This step uses a real-time Delphi study in an interactive workshop format. This method fulfills the purpose of the analysis by enabling an efficient elaboration and discussion of solutions to identified problems (Gerhold, 2019). To draw upon the relevance of the identified effects on different levels, the Delphi study further includes a ranking regarding their challenge to assess and their influence on the total LCA-based impact.

Results

As one key element of the conceptual framework, this dissertation provides a novel taxonomy of environmental effects related to use cases in SES. Published in Publication 1and illustrated in Figure 5, the taxonomy aggregates potential positive and negative environmental consequences of first- and higher-order, distinguishing between the technology, user, and system levels. First-order effects result from the impact of ICT hardware along the product life cycle, i.e., determined through an LCA. As shown in Figure 5, first-order effects occur on the technology level. These can be quantified through an LCA on the required ICT. Effects of higher-order, however, are relevant to all levels. For charging strategies, examples of higher-order effects on the technology level are changes in the operational emissions of BEVs. Concerning the system level, literature on the effects of ICT generally refers to the overall economy or society as a ‘system.’ Applied to use cases in SES in this publication, ‘system’ refers to the energy system. This encompasses two effects: on ‘Generation and Supply,’ e.g., changes in hourly electricity generation and associated emissions, and on ‘Energy Transmission and Distribution (T&D) Infrastructure,’ e.g., electricity grid expansion requirements. To demonstrate the transferability of the taxonomy, the article includes an exemplary description per effect for two of the investigated research projects.

As a first part of the empirical findings, results provide generic research recommendations for each determined environmental effect. These are based on the potential impact on the LCA results and the challenge for assessment. The conducted ranking on the magnitude of consequences on different levels indicates that repercussions within the energy system (system level) potentially cause the highest impact on the total LCA. At the same time, quantifying systemic effects poses the most significant challenges, followed by implications of changing user behavior (user level). Compared to impacts caused by the product or components (technology level), assessing these effects ‘higher-order’ requires additional resources and methods.

The second empirical contribution is the provided map of solution approaches. This dissertation reveals that a holistic assessment of use cases in SES exceeds the capability of the standardized LCA guidelines. Derived recommendations include combining approaches from social sciences (user level) and energy system modeling (system level). Furthermore, a suggested approach is the application of a prospective LCA (pLCA) to consider future developments.

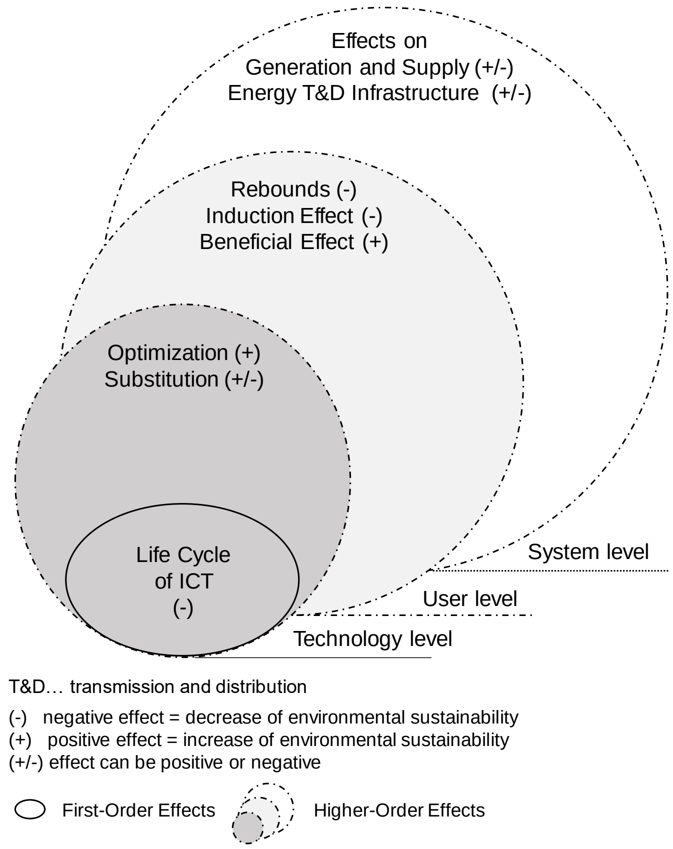

Figure 5: Environmental effects of use cases in SES (Wohlschlager et al., 2023)

Limitations

The taxonomy provides orientation on the complex topic of environmental effects in SES by aggregating multiple effects into those on the technology, user, and system levels. This approach aims to generate a broader understanding of the potential environmental consequences rather than representing exhaustiveness.

The case study approach involves a limited number of investigated use cases and experts. Furthermore, the study acknowledges universal challenges in LCAs, demonstrating its relevance to SES and other fields where LCA is applied. Despite these limitations, the provided map of solution approaches can be used as a starting point for LCAs of emerging technologies in SES and other fields involving higher-order effects. It serves as a foundation upon which subsequent studies can build and refine.

Contribution

First, the developed conceptual framework includes a novel taxonomy on environmental effects relevant to use cases in SES. This overview enhances the understanding of LCA professionals regarding potentially intended and unintended environmental consequences that need consideration when conducting an impact assessment.

Secondly, the developed overview of challenges and respective solution approaches serve as an empirical contribution collected from existing research projects and an expert workshop. This includes suggestions concerning the methodological setup, data gathering, and considering the long-term impacts of currently emerging use cases in SES. The provided recommendations allow LCA professionals to efficiently plan their analyses and resources.

Overall, this dissertation's conceptual framework (Part I) fulfills research objective No. 1 and serves as the basis for elaborating on RQ 1. Results thus offer novel methodological guidance on determining the environmental effects of use cases in SES specifically – a topic not previously explored to this extent but becoming increasingly important with the progressing shift towards SES. The derived approaches for overcoming challenges for a holistic assessment of emerging use cases in SES have been applied in the following parts of this dissertation. Section 3.1 outlines the method development (Part II) and its application for assessing the impacts associated with smart charging of BEVs (Part III).

3 Evaluation of Electric Vehicle Charging Strategies

3.1 Effects on the Technology Level – First-Order

As outlined in the taxonomy of environmental effects of use cases in SES (see Figure 5), the lifecycle impact of additionally required ICT components represents an effect of first-order. Elaborating on research objective No. 2 of determining these effects on the technology level requires an LCA-based assessment of the use cases' ICT compared to a reference case. This section summarizes the developed approach for a comparative LCA (Part II, contribution to RQ 1). This is followed by presenting and discussing the quantitative results of charging infrastructure (EVSE) for smart and uncontrolled charging of BEVs (Part III, contribution to RQ 2). The findings of this analysis are part of Publication 2[3].

Research Aims

This analysis aims to determine and compare the first-order effects of different BEV charging strategies at a household level. The comparative LCA investigates bidirectional (Vehicle-to-Grid, V2G) and unidirectional (V1G) charging infrastructure to uncontrolled charging. As a smart charging use case, CO_2-optimized charging is investigated. The study assumes a conversion to direct current (DC) for the EVSE for V2G charging while charging stations for unidirectional or uncontrolled charging utilize alternating current (AC). With a geographical focus in Germany, the required ICT includes differences in the charging station and implementing iMSys as the mandatory regulatory uniform communication framework within Germany's distribution networks. The study's first aim is to outline the current impact of the ICT infrastructure required per charging strategy. Secondly, the study conducts a pLCA to project the potential reduction in the environmental impact of the private charging infrastructure in the future energy system up to 2040.

Methodological Approach

The methodology follows the four phases of an LCA:

<u>Goal and scope</u>: The FU covers charging a private BEV with a battery capacity of 60 kWh for an operation of one year with an average German driving profile. Besides investigating today's

[3] Wohlschlager, D., Haas, S., & Neitz-Regett, A. (2022). Comparative environmental impact assessment of ICT for smart charging of electric vehicles in Germany. Procedia CIRP, 105, 583–588. https://doi.org/10.1016/j.procir.2022.02.097

CRediT authorship contribution statement: Wohlschlager, D.: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Haas, S.: Investigation, Formal analysis, Writing – original draft, Writing – review & editing. Neitz-Regett, A.: Writing – review & editing, Supervision.

impact (the reference year 2020), a pLCA for 2030 and 2040 is conducted. Following the overall scope of this dissertation (see Section 1.3), the study focuses on the ‘climate change’ impact category (GWP100a). As a charging use case for V1G and V2G, CO_2-optimized charging is assessed. This choice is made to compare the impacts of the ICT infrastructure to the maximum GHG reductions during the operation phase to interpret the results. While V1G and V2G require equal iMSys infrastructure, the regulatory requirements in case of uncontrolled charging depend on the consumer. For the comparative assessment, thus, two scenarios for uncontrolled charging are assessed, i.e., with total annual electricity consumption, including the BEV, exceeding 6,000 kWh (‘MIN’ scenario) and below 6,000 kWh (‘MID’ scenario). Figure 6 illustrates the system boundaries per scenario and charging strategy.

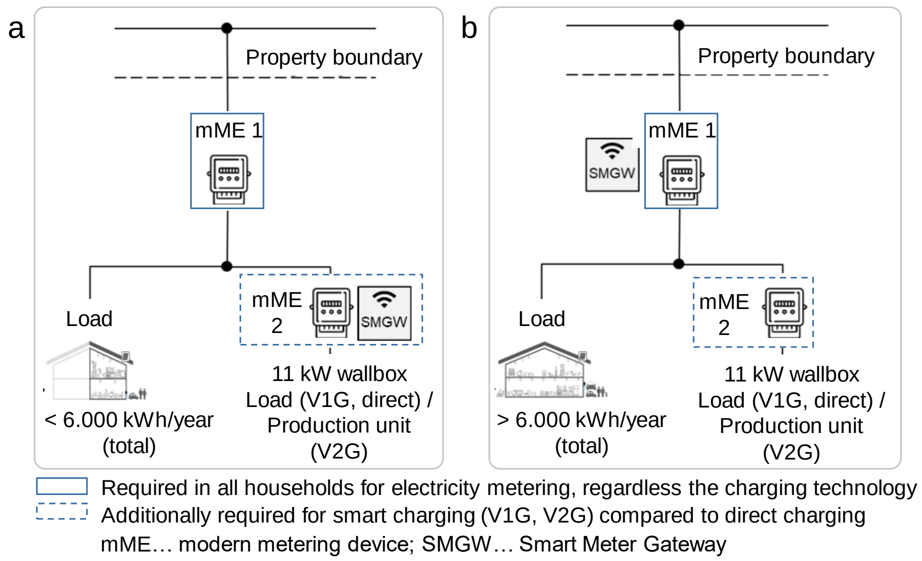

Figure 6: **System boundaries of assessed EVSE (Wohlschlager et al., 2022)**

Inventory Analysis: For the LCI of hardware components, data stems from expert interviews. This is supplemented with secondary data for the wallbox (Bekel & Pauliuk, 2019) and iMSys components (Wohlschlager et al., 2021). The charging profiles for modeling the use phase are derived from Fattler (2021). The prospective emission factor of electricity is determined using a climate policy scenario modeled with an ESM. For data transmission and processing of the use case, input stems from measurements conducted within the research project ‘BDL’ (see Ostermann et al. (2020)). The LCI database ‘ecoinvent’ (Wernet et al., 2016) serves as the basis. For background system adaption for future years, the ‘superstructure approach’ (Steubing & Koning, 2021) is applied as the latest available pLCI database to the publication date.

Impact Assessment: The LCA is conducted with the open-source LCA software brightway2 (Steubing et al., 2020). The study applies the ‘ReCiPe Midpoint (H) V 1.13 no LT’ for the impact assessment.

Interpretation: Sensitivity analyses focus on the hardware's lifecycle phases of production and operation. The first analysis investigates the changing impact over time, e.g., results of the pLCA for the years 2030 and 2040, considering an increasing RE share of German electricity generation for the operation phase. For the example of V2G infrastructure, additional sensitivities explore the potential impact of improved energy efficiency and component longevity. To interpret the first-order effects of ICT infrastructure, the study further compares the LCA results to the consequences of CO_2-optimized V1G and V2G charging on BEV's operational emissions determined by Fattler (2021).

Results

The comparative LCA shows the highest GWP of ICT infrastructure for V2G. For the base year 2020, the annual GWP of V2G charging infrastructure (145.4 kg CO_2e) is 84% higher than V1G charging (79 kg CO_2e). The differences are primarily caused by higher operation times, including hours of discharging and additional power electronics in the DC wallbox. The GWP of uncontrolled charging infrastructure is between 45.2 – 57.5 kg CO_2e per year, depending on the iMSys requirements (see Figure 6).

By 2040, the prospective assessment shows a decrease in the lifecycle impacts by up to 67 % for V1G and 56 % for V2G charging. While the operation phase is the main contributor in the base year 2020, the relevance of lifecycle phases shifts in future years. Sensitivities on efficiency and component lifetime show a higher relevance of the production phase in the coming years. The study recommends manufacturers to focus on a sustainable technical design that also considers the components' longevity.

Lastly, the resulting first-order effects are compared to the achievable reduction of BEV operational GHG emissions of investigated charging strategies, as reported by Fattler (2021). The comparison indicates that the reductions in the impact of BEVs could compensate for the additional impact of ICT on the technology level. A detailed analysis of such effects of higher-order will be investigated in Section 3.2 to further elaborate on RQ 2 of this dissertation.

Limitations

Investigating first-order effects provides an LCA framework and outlines LCI data of private charging infrastructure on a household level, including parameters on ICT operation and data processing. A transfer for assessing other use cases, driving profiles or geographical scopes would require empirical data collection as conducted for this study.

In this LCA, the impact of the investigated EVSE, including metering equipment, is allocated entirely to BEV charging. Suppose these devices also serve other purposes, e.g., electricity metering or controlling other loads or production units. In that case, multifunctionality must be addressed by developing a suitable allocation method for further LCA studies.

The comparison of ICT's first-order effects to reductions in operational emissions of BEVs indicates an overall environmental benefit regarding the reduced GWP. As outlined in the study, however, CO_2-optimized charging strategies might increase peak loads in low-voltage levels, which strain electricity grids. These side effects as of higher-order are analyzed in Section 3.3.

Contribution

As a methodological contribution (Part II), the investigation includes an LCA for the status quo and a pLCA for future scenarios. The methodological steps outlined in Publication 2 can be transferred to assess other use cases in SES. The outlined system boundaries include information on the technical requirements for EVSE for smart and uncontrolled charging in the case of private charging in Germany. Besides the differences between V1G and V2G charging, the presented system architecture illustrates national legal requirements for the standardized iMSys infrastructure. Furthermore, the provided LCI includes empirically collected data on investigated components. LCA practitioners can apply the outlined system boundaries and LCI data to assess other similar use cases in Germany.

Quantified model study results (Part III) provide insights for component manufacturers on the most sensitive parameters and, thus, the most significant levers to reduce the impact. Besides the status quo, the prospective results allow us to prepare for long-term sustainability strategies. Furthermore, the model study shows the quantitative LCA results for the ICT infrastructure of the respective EVSE per use case. It relates these to the potential consequences of respective charging strategies on the operational impact of BEVs. To conclude, the presented elaboration on first-order effects fulfills research objective No. 2 of this dissertation. Comparing the magnitude of the resulting impacts requires considering the repercussions on the overall energy system. Following research objective No. 3, Sections 3.2 and 3.3 investigate such higher-order effects on the system level.

3.2 Effects on the System Level – Higher-Order: Generation and Supply

To elaborate on research objective No. 3, this section investigates the implications of 'Generation and Supply' as one potential systemic higher-order effect of use cases in SES (see Figure 5). This analysis focuses on the impacts of the emission factor of electricity generation. As concluded from the conceptual framework, methodological approaches for assessing the system level involve an expansion of the standardized LCA. Furthermore, future developments need consideration. The method development thus combines a pLCA and scenario modeling using an ESM (Part II, contribution to RQ 1). A subsequent application on smart charging allows us to conclude the systemic effects and the role of smart charging in reaching climate-neutral SES (Part III, contribution to RQ 2). The content of this section is published in Publication 3[4].

Research Aims

To elaborate on the effects of smart charging on electricity generation, the evaluation follows two primary goals. Firstly, it examines how V2G charging affects the electricity system and the resulting life-cycle GHG emissions of electricity generation. Secondly, the consequences of these systemic effects are included in determining the changing operational impact of BEVs. This represents an effect on the technology level of higher-order (cf. Section 2). This interplay between systemic and technological effects is then considered by determining the environmental 'break even,' i.e. when BEVs become environmentally preferable to ICEVs. Combining a pLCA and energy system modeling, the methodological approach aims to consistently consider future developments by harmonizing scenario assumptions to assess the technology and system levels.

Methodological Approach

The methodological steps of the combined approach are as follows:

Goal and Scope: The goal is to assess the environmental impact of using BEVs as flexible storage options from the system and technology perspectives. Following the overall scope of this dissertation, the 'climate change' impact category (GWP100a) serves for evaluation. The study investigates the prospective impacts on electricity generation for 2025 – 2045 for two climate policy scenarios of Germany: the 'V2G' scenario (including BEVs as flexible storage options, price-optimized V2G) and the 'Reference' scenario (stationary BESS only, uncontrolled charging). To assess the implications of systemic effects on the technology level, the study determines the impact of required ICT and the vehicles' operation phase.

Inventory Analysis and Impact Assessment: The core of the methodological development is combining a pLCA approach and scenario modeling with an ESM. For the ESM, 'ISAaR' (Integrated Simulation Model for Plant Deployment and Expansion Planning with Regionalization) is applied. ISAaR is a linear optimization model used to simulate and plan the deployment and expansion of the European energy system (EU27 plus Norway, Switzerland,

[4] Wohlschlager, D., Kigle, S., Schindler, V., Neitz-Regett, A., & Fröhling, M. (2024). Environmental effects of vehicle-to-grid charging in future energy systems – A prospective life cycle assessment. Applied Energy, 370, 123618. https://doi.org/10.1016/j.apenergy.2024.123618

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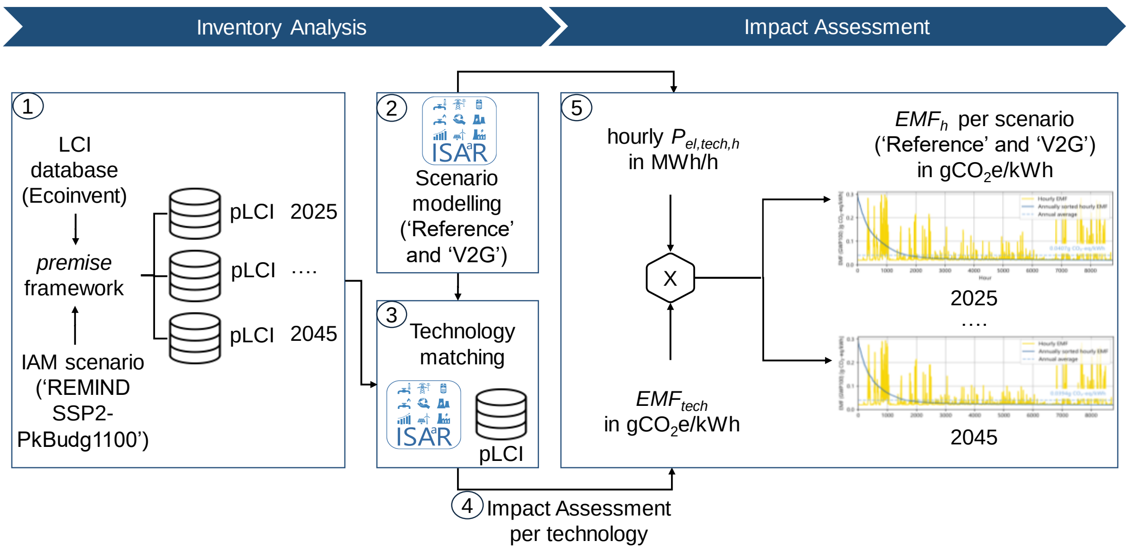
and the United Kingdom), minimizing the total system's costs. When modeling Germany's energy system as the scope of this study, ISAaR considers the interactions within the European market, e.g., by incorporating predefined trading capacities for electricity and hydrogen. ISAaR can also account for non-European countries by including the option to import hydrogen or liquid hydrocarbons. Kigle et al. (2022) outline details on the modeling landscape.

As illustrated in Figure 7, the 'premise' framework (see Sacchi et al. (2022)) serves to adjust the LCI background of the database ecoinvent as a first step. 'Premise' considers future global scenarios using an integrated assessment model (IAM). The climate targets of the selected IAM scenario are consistent with the scenario of the ESM. Sacchi et al.(2022)The Publication 3 describes the challenge of matching technologies between the ESM and the pLCI database and how this is addressed through weighting and modifications. The impact assessment of systemic effects involves determining the hourly emission factors of electricity generation. This is conducted by multiplying the shares of electricity generation per technology with the pLCA-based emission factor per electricity generation technology. For the effects on the technology level, the operational emissions of BEVs per charging strategy are determined using hourly emission factors (resulting from the determined systemic effects) and hourly charging profiles as used in the ESM.



EMF_{tech} … electricity emission factor per technology; EMF_h … hourly EMF per year; ESM… energy system model; IAM… Integrated Assessment Model; $P_{el,tech,h}$… hourly electricity production per technology; pLCI… prospective Life Cycle Inventory

Figure 7: Combination of pLCA and an ESM (Wohlschlager et al., 2024)

<u>Interpretation</u>: The results of the systemic effects are discussed by comparing total GHG emissions, average emission factors, and standard deviation of hourly emission factors between scenarios and over time. The technology level assessment focuses on the annual operational emissions per BEV and the environmental break-even with ICEVs. This is the point (in time or

kilometers) at which the cumulative reduction in operational impacts of BEVs offsets their higher footprint in the production phase.

Results

Regarding the changes in the energy system over time, the ESM depicts an increase in electricity generation from approx. 600 – 1,240 TWh for the modeled time frame of 2025 – 2045. Both scenarios reach the climate targets and a 100% RE share by 2045. However, additional storage capacities from BEVs in the ‘V2G’ scenario accelerate the RE integration in the medium-term (2030 – 3035). As impacts on the system level, results conclude that V2G charging offers a relevant flexibility option, serving as a bridge to accelerate the transition towards an SES based on volatile RES. Besides slightly lower total emissions of national electricity generation, the additional storage capacities of V2G further decrease hourly emission peaks compared to the reference case. However, from 2040 onwards, V2G charging has no impact on any indicator of GHG emissions compared to a scenario with uncontrolled charging and only stationary BESS. Here, the differences mainly concern the required stationary BESS capacities. A substitution of 117 GWh of stationary BESS in the ‘V2G’ scenario indicates a reduction in raw material requirements.

The investigation of the operational impact of BEVs considers the interplay of effects on the system level. Assuming an operation of a BEV in the ‘V2G’ scenario, the analysis concludes with a shorter environmental amortization time (‘break-even’) regarding the GWP in the cases of V1G and V2G compared to uncontrolled charging. Here, the study includes two methods for dealing with the allocation in case of discharging, i.e., in- or excluding systemic reductions being credited to the BEV’s operational impact. Including systemic reductions refers to a system expansion, while an exclusion corresponds to a physical allocation. Considering systemic reductions, the most significant decrease in annual operational emissions occurs by 2030. Compared to uncontrolled charging, V2G reduces operational emissions by approx. 200 % and reaches net negative values of - 141 kgCO_2e per BEV. This potential by 2030 occurs because of the high availability of charging hours with nearly zero emissions from RE while discharging substitute electricity generation during periods with high GHG intensity. As the RE share increases over time, the potential of shift charging into GHG-intense hours diminishes (e.g., reaching - 0.1 kgCO_2e/BEV in 2045).

Figure 8 exemplarily illustrates the effects on the break-even for mid-sized passenger cars over time for this dissertation’s scenarios and underlying assumptions. In the case of uncontrolled charging, the break-even in this example occurs after 3.0 years (approx. 42,180 km). This is reduced to 2.7 years (approx. 38,410 km) for V2G with physical allocation, which equals V1G charging. When considering systemic reductions of V2G, the break-even in this analysis occurs after 2.5 years (approx. 34,980 km). While uncontrolled charging causes 15.6 tCO_2e during the operating period from 2025 – 2035, systemic reductions from V2G result in a net decrease of operational emissions, e.g., - 0.3 tCO_2e. Despite this net decrease in the BEV's impact, however, V2G cannot compensate for the production-based impact of a mid-sized BEV (i.e., 12.8 tCO_2e (Buberger et al., 2022)).

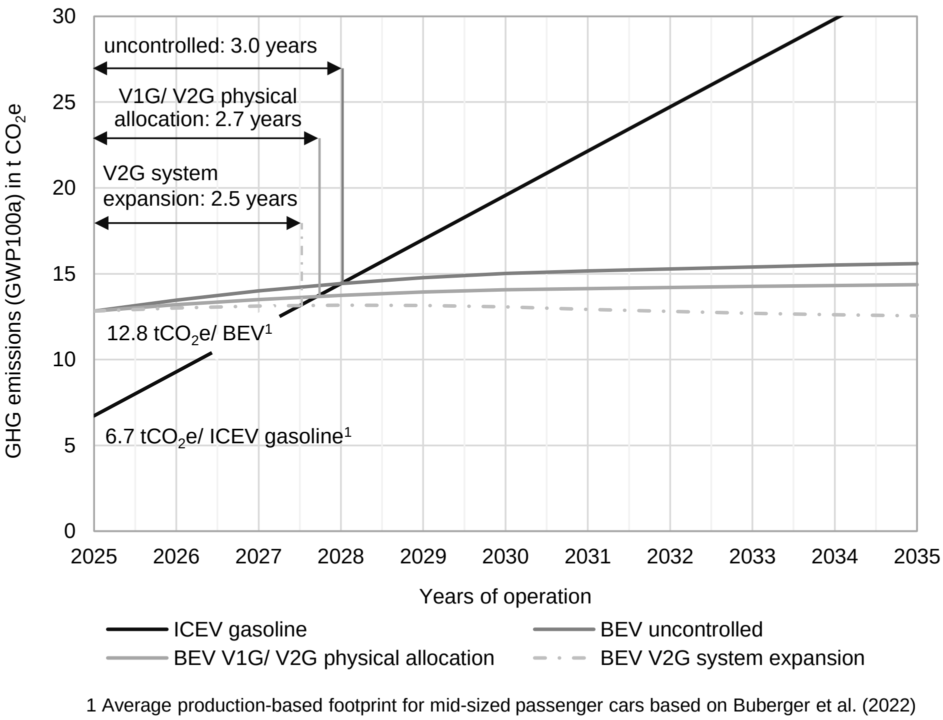


Figure 8: Exemplary break-even of BEVs and ICEVs (Wohlschlager et al., 2024)

Limitations

In line with the geographical scope of this dissertation, the study evaluates the case of the German electricity system. While the investigation excludes an impact assessment for other countries, the scenarios are modeled with a cost-optimized European ESM and thus indirectly include repercussions within the European system within the results for Germany.

The 'V2G' and 'Reference' scenarios used in the study are extreme cases but fulfill the purpose of investigating the potential of using BEV batteries as a flexible storage option. In the V2G scenario, a high capacity is provided by BEVs as flexible storage options. The charging strategy is price-optimized based on the spot market price, i.e., energy arbitrage. Future business models of V2X might enter the system, which are not considered in these scenarios. Therefore, the resulting values must be regarded as a comparative indicator of the impacts of investigated charging strategies resulting from the scenario assumptions rather than in absolute numbers.

Regarding the technological scope, the study focuses on all-electric vehicles only due to their relevant flexibility and potential to interact with the electricity system. Lastly, the literature indicates that charging strategies influence battery degradation. Besides the consequences on the life-cycle-based impact of BEVs, changes in the available battery capacity affect systemic repercussions. Implementing battery aging into the ESM should be considered for further research. These limitations are further discussed in Section 4.1.

Contribution

As a contribution to the method development of this dissertation (Part II, contribution to RQ 1), the innovation lies in its comprehensive assessment of higher-order effects on the system level and considering interactions with the technology level. The combined approach of a pLCA and energy system modeling consistently considers future developments in the energy system landscape and the technologies' LCI. The outlined method for determining systemic effects on electricity generation can be transferred to assess other geographical areas or use cases in SES.

Quantified results outline and discuss the role of V2G in reducing the medium- and long-term climate impact of electricity generation (Part III, contribution to RQ 2). Results further indicate the changing demands of alternative electrical storage capacities and discuss potential environmental impacts related to resource depletion and mineral resource scarcity. By considering systemic effects when assessing the operational impact of BEVs, results provide insights for manufacturers on the expected future impacts. The analysis reveals potentials of V2G to accelerate the environmental 'break-even' in the medium-term. It further highlights the relevance of improving production processes to decrease lifecycle impacts in the long-term.

3.3 Effects on the System Level – Higher-Order: Electricity Infrastructure

Next to systemic effects on 'Generation and Supply' as presented in Section 3.2, the final analysis of this dissertation further contributes to research objective No. 3 by determining effects on 'Energy T&D Infrastructure.' In line with the scope of the previous investigations and due to the relevance in the context of smart charging strategies, the following section elaborates on the electricity system. Similar to Section 3.2, this analysis includes a method development that combines a pLCA and scenario modeling (Part II, contribution to RQ 1), followed by a quantitative study on smart charging (Part III, contribution to RQ 2). The content of this section is part of the Publication 4[5].

[5] Wohlschlager, D., Reinhard, J, Stierlen, I., Neitz-Regett, A., & Fröhling, M. (2024). Green light for bidirectional charging? Unveiling grid repercussions and life cycle impacts. Advances in Applied Energy, 16, 100195. https://doi.org/10.1016/j.adapen.2024.100195
CRediT authorship contribution statement: Wohlschlager, D.: Conceptualization, Methodology, Investigation, Formal Analysis, Validation, Data Curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. Reinhard, J.: Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. Stierlen, I.: Investigation, Writing – original draft. Neitz-Regett, A.: Writing – review & editing, Supervision. Fröhling, M.: Writing – review & editing, Supervision.

Research Aims

This investigation addresses the effects of different charging strategies on electricity infrastructure. The primary goal is to develop a suitable method that is subsequently applied to quantify the prospective lifecycle impacts of repercussions within distribution grids in the low-voltage levels. Secondly, the study aims to determine the magnitude of these systemic impacts compared to environmental effects on the technology level of first- (ICT infrastructure) and higher-order (operational impact of BEVs). By doing so, the aim is to conclude on RQ 2 and to derive insights for researchers, policy, and industry on expected future implications of charging strategies on different levels, the comparative magnitude, and major levers for an impact reduction.

Methodological Approach

The LCA-based evaluation of higher-order effects on electricity grids is conducted as follows:

Goal and Scope: The comparative LCA aims to quantify the prospective environmental impacts of reinforcement requirements in the distribution grid depending on the charging strategy. The systemic effects are determined for a rural distribution grid area in Bavaria, Southern Germany, for 2040 (the target year for reaching climate neutrality in Bavaria). Three scenarios with differing shares of charging strategies are simulated: the ‘Baseline’ scenario (100 % uncontrolled charging), the ‘V2G’ scenario (100 % price-optimized V2G), and the ‘Mixed’ scenario (17 % price-optimized V2G, 19 % V2H in combination with a PV system, 64 % uncontrolled charging). The FU comprises the difference of the annual grid expansion requirements within the investigated grid area by 2040 for the ‘V2G’ and ‘Mixed’ compared to the ‘Baseline’ scenario. Quantified effects on the system level are compared to those on the technology level, i.e., the operational emissions per BEV and required ICT. The FUs cover the annual electricity for charging and discharging for operation in Germany (operational emissions, analog to Publication 3) and the charging infrastructure for private charging of one BEV per year (required ICT, analog to Publication 2). In line with the scope of this dissertation, the analysis focuses on ‘climate change’ (GWP100a) to compare the effects.

Inventory Analysis: The grid expansion requirements per scenario are determined with the techno-economic simulation model ‘GridSim’ (details in Müller et al. (2020)). LCI data on investigated distribution grid components (transformers and grid lines) stems from literature as a starting point. This is supplemented by empirical data collected from manufacturers and grid simulations. The analysis uses the LCI database ‘ecoinvent,’ version 3.8, as the basis. Analog to the pLCA approach in Publication 3, ‘premise’ serves as a background system adaption for generating the pLCI database for 2040. The operation phase of investigated components encompasses their power losses derived from the simulation model. The national average electricity emission factor by 2040 is determined following the method outlined in Section 3.2.

Impact Assessment: The focus of the analysis and the comparison of the effects of the technology level is on climate change. The systemic effects of distribution grids are further assessed for all impact categories of the 'ReCiPe Midpoint (H) V 1.13 no LT' method, except marine ecotoxicity (high degree of uncertainty (Jorge et al., 2012)) and ionizing radiation (power grids involve non-ionizing radiation (Jorge & Hertwich, 2014)).

Interpretation: Determined annual impacts of distribution grid expansion by 2040 are outlined as total values per impact category, contribution per component, and life cycle phase. This is followed by a sensitivity analysis for the most contributing life-cycle stages. Lastly, the effects on the system level, i.e., distribution grids, are compared to the impacts on the technology level. This includes the required ICT per charging strategy (first-order) and operational emissions of BEVs (higher-order). To bring the effects on different levels into relation, total impacts are transferred into the impact per BEV in the investigated distribution grid by 2040.

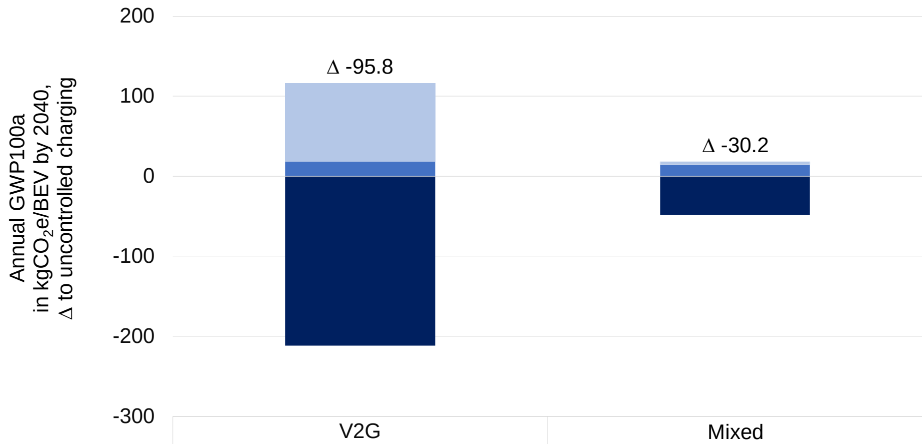
Results

First, the modeling results show the share of grid overloads in the investigated grid area depending on the charging strategy. Here we have to note that these overloads would only occur if no other mechanisms would be in place. In reality, the grid operator will have the option of restricting individual consumers in order to avoid overloading the grid. The following results are thus only theoretical values in case of no other mechanisms in place.

For the 'Baseline' scenario, the grid simulation shows that 45.6% of grids will be overloaded by 2040. These overloads occur mainly during evening peaks when uncontrolled charging is assumed. The 'V2G' scenario sees an overload in 71.3% of grids. Applying a price-optimized bidirectional strategy, this increase results from higher charging simultaneities and increased energy exchange between BEVs and the grid. This scenario also shows significant increases in grid line expansion (+280%) and transformer replacements (+130%) compared to the 'Baseline' case. Although the 'Mixed' scenario causes slightly fewer grid overloads than the 'Baseline,' power losses in grid lines are higher due to the increased energy exchange. Compared to the 'Baseline' scenario, pLCA results conclude on an additional GWP of 97.8 ('V2G') and 3.4 kg CO_2e/a per BEV ('Mixed') by 2040. The power losses represent the main contributor to the impact across all impact categories. Variations of the emission factors of electricity in the sensitivity analysis show that a higher RE share can decrease the impacts in most impact categories. Interestingly, this leads to slightly higher values in other impact categories, e.g., human toxicity and impacts related to water or metal depletion, due to the upstream chain of RE generation technologies.

The second part of the study compares these systemic effects on distribution grids to effects on the technology level (ICT infrastructure, operation phase of BEV). Compared to uncontrolled charging ('Baseline'), the sum of impacts on the technology and system levels show that bidirectional charging leads to a net decrease of the GWP with - 95.8 ('V2G') and

- 30.2 kg CO_2e/a per BEV (‘Mixed’) by 2040. As illustrated in Figure 9, lower impacts during the operation phase compensate for the higher impacts caused by systemic effects on the distribution grid and by ICT infrastructure for EVSE. While price-optimized V2G charging leads to the highest impact reductions during operation, even reaching negative values (- 211.8 kg CO_2e/a per BEV), the determined high grid reinforcement requirements for large-scale implementation of V2G charging may not be technically or economically feasible. The article recommends diversified charging strategies, such as the ‘Mixed’ scenario, i.e., a combination of V2G and V2H. Overall, the results displayed in Figure 9 are based on the underlying assumptions in the energy system models and scenarios and thus involve uncertainties. These are further discussed in Section 4



	V2G	Mixed
Distribution Grid	97.8	3.4
ICT Infrastructure	18.3	14.9
Operation Phase BEV	-211.8	-48.5

Figure 9: Exemplary effects on different levels for the ‘V2G’ and ‘Mixed’ scenarios, 2040 (Wohlschlager, Reinhard et al., 2024)

Limitations

The study is based on a case of rural distribution grids in Southern Germany. The results are consequently not representative due to local conditions and building structures. The comparative study, however, offers insights into the magnitude of systemic effects caused by different charging strategies. Researchers can apply the outlined methodological steps to investigate other grid areas and use cases.

Next, the static techno-economic simulation excludes feedback on the electricity market or the price signal. The simultaneity of BEV charging processes and, thus, the absolute values of the pLCA might be overestimated, especially in the case of V2G. Nevertheless, the results provide a feasible indicator for the comparative impacts of different charging scenarios.

Recommendations for further research include expanding the model with more detailed analyses of the plug-in behavior of end users and how this affects the grid repercussions. Following the conceptual framework of this dissertation, this would represent an effect on the user level (see Section 2). Furthermore, an expansion to investigating the effects of medium-voltage level poses an open research question. While this study focuses on environmental assessment, an economic evaluation of the utilization of BEVs and the associated need for grid expansion is out of scope. A comparison to alternatives like stationary BESS or large-scale flexibilities at higher voltage levels is recommended.

Contribution

Overall, this final investigation complements the previous analyses of this dissertation by investigating the systemic effect on ‘Energy T&D infrastructure’ and by bringing together the other investigated effects into one comparison. As a methodological development (Part II, contribution to RQ 1), the article provides the required steps to combine techno-economic modeling of distribution grids and a pLCA with consistent integration of future developments. The exemplary scenario-based assessment of a rural distribution grid area in Southern Germany proves the method's suitability. Researchers can apply the outlined methodological steps to assess other grid areas and use cases.

Quantified results show the systemic consequences of different charging strategies and their magnitude compared to effects on the technology level (Part III, contribution to RQ 2). Although the quantitative results of the case study are not representative of electricity distribution grids in general, this assessment sheds light on the impacts on local infrastructures depending on the charging strategy. The outlined possible levers for minimizing these impacts can be investigated for individual grid situations. Lastly, bringing together the determined impacts of smart charging on different levels provides insights into the relevance of these effects. Results on the most severe effects in future energy systems can be considered for sustainable energy system planning before large-scale deployment.

4 Discussion

With the ongoing transformation towards SES, novel use cases emerge. When it comes to the assessment of associated lifecycle impacts, previous environmental evaluations show the need to expand the standardized LCA method. In three parts, this dissertation answers two main research questions and elaborates upon three research objectives (cf. Section 1.5). In response to RQ 1, this work contributes to the scientific literature by providing a conceptual framework (Part I) and methodological approaches (Part II) for a holistic lifecycle-based impact assessment. To elaborate on RQ 2, the developed methods are validated by using the example of charging strategies of BEVs (Part III). Section 4.1 discusses the resulting core findings and contextualizes these in the scientific literature. Section 4.3 points out the limitations of this work and areas for further research. Finally, Section 4.3 highlights the relevance for stakeholders that can build upon this work.

4.1 Findings and Contribution to Literature

The established conceptual framework of this dissertation contributes to the research field of 'ICT4S'. Studies in this field have already highlighted the need for combining LCA with system modeling to determine the impact of ICT (Hilty & Aebischer, 2015; Pohl et al., 2019). This dissertation transfers these approaches specifically for assessing ICT in the context of energy systems. The resulting framework outlines a holistic picture of the potential intended and unintended impacts of novel use cases, specifically in SES. Previous investigations primarily focus on evaluating single effects, e.g., from the technology or system point of view, and faced challenges during the LCA. Reported obstacles to quantifying these effects occurred when defining the goal and scope, collecting data, or considering future developments consistently. The determined solution approaches fulfill research objective No. 1 of this dissertation to guide future analyses of SES. Derived recommendations serve as a starting point for the translation into quantitative methods in the second part of this dissertation.

The methods developed in this work allow for quantifying the effects of use cases in SES of first- and higher-order. Resulting approaches show that technological impacts of first-order effects can be determined following the standardized LCA while assessing higher-order effects requires enhanced methods. With a focus on use cases in SES, this involves the combination with energy system modeling. While approaches to combining LCA and scenario modeling with an ESM have been continuously developed, the novelty of this dissertation's approaches lies in assessing the impact of novel use cases. Due to the emerging character, this demands considering future developments through a pLCA approach. Furthermore, effects must be determined in an hourly resolution (e.g., on the GWP of electricity generation). The latter is required to conclude the interplay between systemic and higher-order effects on the technology level. To guarantee comparability of effects on different levels, this work consistently considers future developments on various levels (e.g., electricity generation, grids, and technologies) by harmonizing the scenario assumptions and LCI background adjustments across these levels. The outlined methodological steps thus represent a consistent, future-oriented setup for a holistic evaluation of use cases in SES.

While the answer to RQ 1 of this dissertation provides solution approaches for assessing use cases in SES, specific challenges (e.g., evaluating effects of higher-order, dealing with data gaps) also occur for LCAs in other fields. Frischknecht et al. (2016) outline the importance of the transferability of LCA methods across contexts, emphasizing the need for flexibility in assessing environmental impacts. Therefore, the outlined conceptual framework and methods offer starting points to overcome the challenges of LCAs in other fields.

Concerning RQ 2, previous assessments of smart charging have continuously highlighted the benefits of integrating RE, especially when using the flexibility potential of bidirectional charging (Lund & Kempton, 2008; Noel et al., 2019). While RE integration can be classified as one intended benefit from the systemic perspective, this work enhances the overall picture by shedding light on the magnitude of effects on different levels. Results encompass the impacts caused by ICT for EVSE (technology level), systemic repercussions on the electricity system (system level), and how this affects the operational emissions of BEVs (interplay between system and technology level). Using Germany's energy transition as an example, the study explores the role that BEVs can play through ICT-enabled use cases.

First, research objective No. 2 elaborates on the effects of smart charging on the technology level. On the one hand, results show that EVSE for uni- and bidirectional charging involves higher impacts of first-order than uncontrolled charging. On the other hand, charging strategies can lead to an overall reduction in the GWP of BEV operation as a technological effect of higher-order. Besides CO_2-optimized charging strategies, this has also been shown for strategies following the spot market price (energy arbitrage). The reduction potentials result from the consequences on electricity generation as elaborated in research objective No. 3, i.e., as an effect on the system level. As a result of the price-optimized climate policy scenario modeled with an ESM, V2G offers a flexibility option that accelerates the RE integration, which is in line with the literature (see review by Pearre and Ribberink (2019)). Despite the slightly higher integration of RE, the effects of charging strategies on total national electricity generation emissions are relatively marginal. These results align with a recent study by Will et al. (2024) on the effects of unidirectional smart charging on Germany's electricity system by 2030. Although concluding on lower curtailment of RE, the study outlines insignificant impacts on total GHG emissions. From 2030 onwards, the results of this dissertation show that the systemic effects of charging strategies on the GHG intensity of electricity further diminish.

While V2G offers the potential to reduce BEV's operational emissions in the medium-term, this work concludes that the current production-based impact of BEVs cannot be compensated over the vehicles' lifetime for an average German driving profile. The determined reduction potentials, however, strongly depend on the underlying modeling assumptions. First, this dissertation assumes optimized charging from a systemic perspective, e.g., resulting from the cost-optimized ESM. Secondly, the ‘V2G’ scenario is applied to determine the operational emissions of BEVs in future years. The repercussions of a large-scale penetration of V2G charging are thus considered, which cause changes in the spot market and the resulting hourly emission factors. The methodology for determining hourly emission factors developed in this dissertation is applied in a study by Vollmuth, Wohlschlager, et al. (2024) to assess operational emissions of various V2X use cases, including price-optimized V2G. Here, the underlying scenario excludes any flexibility availability from BEVs or stationary BESS and the associated repercussions on the spot market. Also, the cost optimization is conducted from a user perspective rather than an energy system perspective. For V2G charging, the study concludes with annual operational emissions of - 267 kgCO_2e per BEV by 2030 (i.e., compared to - 141 kgCO_2e per BEV determined in this dissertation, see Section 3.2). Therefore, the values presented in this dissertation must be seen as an indication for comparing the impacts of charging strategies in a particular scenario with the respective underlying assumptions rather than in absolute values. As conducted by Vollmuth, Wohlschlager, et al. (2024), researchers can apply the provided method of this dissertation to assess other scenarios and use cases.

Despite the benefits on RE integration and BEV’s operational impacts, analyses of this dissertation show that V2G can cause significant repercussions on distribution grid infrastructures. This is especially the case for a high penetration of price-optimized charging strategies. Besides this extreme scenario, the simulations show that applying a mix of uni-, bidirectional, and uncontrolled charging strategies can significantly decrease the strains on local grids. Accordingly, balanced charging strategies are relevant for reaching an electrification of passenger transport with low climate impacts.

4.2 Limitations

As a limitation and source of uncertainty within the provided methods, determining the medium and long-term impacts inherently involves assumptions on technological advancements. The complexities involved with modeling future energy systems are widely acknowledged, and the importance of transparency has been highlighted in the literature (Bistline et al., 2021; Cao et al., 2016). While predicting the future remains challenging, the publications of this work outline the modeling assumptions of applied ESMs and critically reflect on the limitations of scenario-based assessments. Further research can build upon outlined methods to assess other scenarios and geographical scopes using differing modeling assumptions.

Regarding the model study, the assessment focuses on the impact category of climate change. Other impacts are only partly addressed in the dissertation’s publications as an aside or outlook. This includes systemic long-term effects on the changing demand for stationary BESS as an alternative storage option to BEV batteries. Results of the ESM show a decrease of up to 117 GWh of stationary BESS capacities in the case of a large-scale application of V2G. Although not quantified in this dissertation, studies indicate that using BEV batteries as a flexible storage option or as repurposed batteries in the energy system could not only decrease impacts on climate change but also yield savings in resource depletion and mineral resource scarcity (Koroma et al., 2022; Schulz-Mönninghoff et al., 2021). Besides these potential benefits, the literature highlights that technologies involved in the transition to climate neutrality cause other trade-offs in sustainability, e.g., on land use, the biosphere, and local social systems. (Creutzig et al., 2024) Further research can build upon this dissertation's conceptual and methodological approaches to expand the evaluation of use cases in SES.

Another limitation is the exclusion of considering battery degradation as an effect on the technology level. Especially in the context of V2X use cases, the impact on batteries is widely discussed in literature and industry. Gschwendtner et al. (2021) summarize findings ranging from uncertain or negligible effects on battery degradation to potential benefits on battery lifetimes. Rücker et al. (2024) highlight that data on battery operation, capacity tests, mobility patterns, and charging curves is required to determine the impact of V2X on battery aging, which has been sparely monitored in previous field tests. A recent experiment by Gong et al. (2024) finds that V2X has no substantial impact on battery aging and might even reduce battery capacity loss compared to uncontrolled charging. However, the effects on battery degradation strongly depend on the underlying charging assumptions. Influencing factors include the maximum charging and discharging power, battery size, SoC range, and the desired SoC at departure (Gong et al., 2024). Future research should build upon these studies to consider battery degradation when assessing the lifecycle impacts of particular charging strategies.

Lastly, the model study and methods provided for quantifiying environmental effects are limited to the technology and system levels. This dissertation excludes the provision of novel approaches to evaluate effects on the user level. As one example of behavioral effects of smart charging, driving patterns influence the flexibility potential of BEVs, e.g., parking duration and desired SoC at departure. (Huber et al., 2019). Changing assumptions on the flexibility potential affects the system level (e.g., on repercussions within the electricity system), which impacts the technology level (e.g., operational emissions of BEVs). Future research needs to investigate potential rebounds, and beneficial or induction effects. As summarized and described as part of the conceptual framework in Wohlschlager et al. (2023), solution approaches include modeling of user scenarios by using data from surveys, panels, or measurements within field trials.

Overall, this dissertation is significant for various stakeholders within the field of SES. This section outlines that the generally applicable methodological contribution contributes to scientific literature. Specifically, results benefit researchers dealing with lifecycle-based impact assessments of ICT (Part I: conceptual framework) and the combination of LCA and energy system modeling (Part II: method development). Furthermore, the quantified impacts for the example of charging strategies (Part III: model study) hold significance for policy and industry. Section 4.2 summarizes insights on what must be considered for large-scale charging strategy integration when aiming for climate neutrality.

4.3 Significance for Policy and Industry

With regard to energy system planning, this dissertation recommends that policymakers foster the application of charging strategies as an enabling technology for the transition toward climate-neutral SES. In line with previous literature, this work shows that V2G charging enables the utilization of the growing number of BEVs as a flexible storage option. Such flexibility options are increasingly required in an SES characterized by fluctuating RE generation and increasing loads from electrification measures. Results of the model study indicate that using charging strategies contributes to reaching the Government’s target of electrification in the transportation sector while accelerating the integration of RE in the medium-term. Besides these benefits, applying the conceptual framework provided in this work reveals that charging strategies potentially cause unintended negative impacts. From a systemic perspective, this includes repercussions on electricity grid infrastructures. The resulting increased demand for grid expansion causes environmental impacts and increases the overall challenge of grid reinforcements required for the energy transition. Policymakers should implement suitable regulatory conditions for a sustainable large-scale penetration of BEVs that avoids such impacts. This includes fostering the digitalization of distribution grids to allow the monitoring of local grid restrictions.

Recommendations for the industry address the automotive sector’s original equipment manufacturers (OEMs), manufacturers of required ICT, and service providers of new charging business models. Results reveal a comparatively higher impact of EVSE required for controlled charging. Especially in the medium-term, the impact reductions during the operation phase of BEVs can compensate for these impacts. To guarantee sustainability in the long-term, OEMs and manufacturers of ICT should focus on decreasing the impacts of the production phase and along the supply chain. Furthermore, the positive contributions from a systemic perspective depend on the flexibility potential of BEVs. Industry can contribute to increasing the potential through technical advancements, e.g., charging power and minimizing effects on battery aging. Large-scale integration of charging strategies further requires the continuous testing of norms for interoperability of technical components, e.g., in the EV, charging infrastructure, and metering point operators (Vollmuth, Hawran, et al., 2024).

Besides technical parameters, the right incentives must be in place to guarantee user acceptance to apply charging strategies. Studies on users’ motivation conclude that currently experienced BEV users, i.e., innovators and early adopters, prefer charging strategies contributing to climate neutrality (Baumgartner et al., 2022), RE integration, and grid stability (Kubli, 2022). For an uptake of charging strategies, the authors recommend communicating environmental benefits. The high relevance of a ‘green’ energy source and regionality is also found in a German study on consumer awareness and preferences for carbon-neutral charging strategies (Will et al., 2022). The provided methods and quantified results of this dissertation can serve as inputs to quantify and report on the environmental benefits, thus contributing to the uptake of smart charging. For a large-scale adaption of charging strategies, the abovementioned studies conclude that monetary benefits gain relevance. Besides the initial investment costs for BEV owners, V2X offers promising revenue potential. Case studies show this is especially the case when combining charging strategies (multi-use), such as V2H and V2H (Ghatikar & Alam, 2023; Kern et al., 2022). Vollmuth, Wohlschlager, et al. (2024) conclude that various multi-use combinations are already profitable today and will create even higher revenues in 2030. This strengthens the recommendations from this dissertation to promote the development of diverse charging use cases. Combining use cases can decrease the systemic impact on local grid infrastructures and increase consumer acceptance.

Regarding the investment efforts of different stakeholders, BEV owners who use V2G charging invest in a BEV and often in private EVSE, but also provide flexibility to the energy system. On the other hand, utility companies must facilitate the provision of attractive V2G products and services and invest in required infrastructures. Therefore, the integration of V2G requires a collaborative effort between BEV owners and utility companies. To realize sufficient consumer incentives, policymakers should create suitable conditions, including regulations for discharged electricity (Vollmuth, Wohlschlager, et al., 2024). Concerning social justice, Will et al. (2024) conclude that regulators should encourage investments in RE and flexibility options. As the share of RE increases, flexibility aggregators can leverage lower electricity purchasing costs to benefit users of smart charging. The authors argue that less curtailment of RE, achieved by aggregators through optimal charging, can ultimately lower electricity prices for all consumers.

5 Conclusions and Outlook

While the benefits of ICT-enabled use cases for the transformation towards climate-neutral SES are widely acknowledged, a large-scale implementation can involve adverse environmental impacts. A missing overview of potential environmental consequences and ways for quantification was the starting point for this dissertation. As a methodological contribution, this work provides a conceptual framework and approaches for a holistic assessment of lifecycle impacts associated with use cases in SES. To prove their suitability, developed methods are applied to assess charging strategies of BEVs in Germany. Findings provide insights for research, industry and policy on the role of uni- and bidirectional charging for reaching the goal of climate neutrality in the medium- and long-term.

In response to the first research question, the developed conceptual framework shows environmental impacts on the technology, user, and system levels. Additionally, the required ICT infrastructure represents an effect of 'first-order' on the technology level and can be assessed through the product-oriented LCA method. However, the effects of 'higher-order' require the expansion of the standardized LCA. This includes determining energy system-wide consequences resulting from a large-scale application of currently emerging use cases and how these affect the future impacts on the technology level. By combining approaches of a pLCA with energy system modeling, the developed methods consistently consider future developments on the technology and system levels. Thus, research dealing with the assessment of emerging technologies in SES can build upon the methodological contribution of this work.

Results on the second research question provide quantitative results on the impacts of climate change associated with charging use cases of BEVs. The comparative investigation considers use cases of uni- and bidirectional charging compared to uncontrolled charging. Results indicate a higher impact on climate change as an effect of first-order, caused by the required charging infrastructure. Compared to direct or unidirectional charging, this additional impact can be compensated by the potential reduction of operational emissions for V2G charging (e.g., CO_2- or price-optimized strategies). While the highest potential to decrease operational emissions occurs in the medium-term, manufacturers should also strive for a sustainable product design and longevity of components for long-term sustainability. From a systemic point of view, recommendations for industry and policy include maximizing the technical flexibility potential (e.g., charging power, minimizing effects on battery degradation) and user incentives (e.g., reporting environmental benefits, offering revenue potentials). Besides contributing to an accelerated integration of RE in the medium-term, modeling results indicate that the flexibility potential of BEVs can essentially substitute the demand for stationary BESS in the long-term. While single strategies such as price-optimized V2G charging cause significant repercussions on low-voltage grids, this can be decreased by balanced charging strategies and considering local grid restrictions. Policymakers must foster the digitalization of distribution grids and enable various charging strategies to efficiently use the flexibility potential of BEVs as one element of climate-neutral SES.

To conclude, this dissertation fulfills the overall goals of enhancing the methodological approaches to assess the environmental effects of emerging technologies in SES and to provide quantitative insights on the magnitude of these effects. As a result of RQ 1, the offered conceptual framework and the developed methods allow us to consistently consider future developments when identifying medium- and long-term impacts of novel use cases. Concluding on the expected impacts and the major levers for minimizing these impacts can serve as the basis for sustainable energy system planning before large-scale deployment. Validated on a model study of smart charging of BEVs, the quantified results of RQ 2 offer insights for industry and policymakers on their role in achieving climate-neutral SES. Results show that when implemented strategically, bidirectional charging can provide a relevant flexibility option that accelerates the integration of RE while reducing impacts on climate change.

Future research can build upon this dissertation to expand the evaluation of use cases in SES. As presented in the taxonomy of environmental effects, this includes investigating effects on the user level. While the quantitative assessment in this dissertation focuses on the technology and system levels, the conceptual framework includes approaches for considering user behavior. Researchers can build upon the provided recommendations for dealing with these effects, including investigating rebounds, beneficial, and induction effects. Furthermore, this dissertation's quantitative model study focuses on the impacts of climate change. Future research can apply the developed methods to assess other impact categories. Next, the outlined approaches allow LCA professionals to evaluate different scenarios and use cases in SES.

Overall, considering future developments and the magnitude of effects on different levels is a first step for a sustainable large-scale application of novel use cases. This dissertation enhances the conceptual understanding of other environmental impacts, including their interactions, and provides methodological approaches for quantification that consistently consider future developments. Supplemented with a model study, this work outlines charging strategies' potential role in reaching climate-neutral energy systems. With the hope that this work catalyzes further research and innovation, we look optimistically at a future where sustainable energy systems are not just a possibility but a reality.

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Annex

A1 Publications of this cumulative dissertation

Publication 1: Wohlschlager, D., Bluhm, H., Beucker, S., Pohl, J., & Fröhling, M. (2023). Overcoming challenges in life cycle assessment of smart energy systems – A map of solution approaches. *Journal of Cleaner Production*, *423*, 138584. https://doi.org/10.1016/j.jclepro.2023.138584

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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

A R T I C L E I N F O

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A B S T R A C T

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

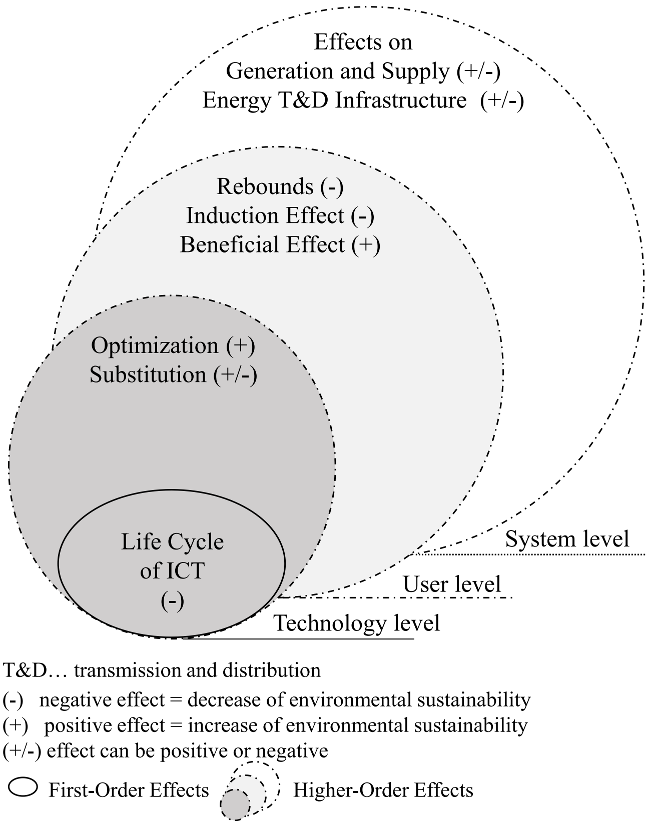

Fig. 1. Environmental effects of ICT on different levels, applied for SES (modified after Pohl et al. (2019)).

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.

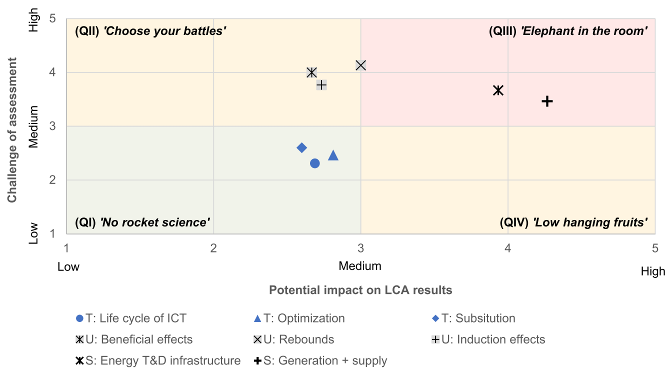

Fig. 2. Ranking of environmental effects based on potential impact and challenge of assessment resulting from the Delphi (T = Technology; U = User; S = System).

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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Comparative environmental impact assessment of ICT for smart charging of electric vehicles in Germany

Daniela Wohlschlager*[1,2], Sofia Haas[1], Anika Neitz-Regett[1]

[1]*FfE, Am Blütenanger 71, 80959 Munich, Germany*
[2]*TUM School of Engineering and Design, Technical University of Munich, Arcisstraße 21, 80333 Munich, Germany*

* Corresponding author. Tel.: +49 (0)89 158121-60. *E-mail address:* dwohlschlager@ffe.de

Abstract

This study examines the environmental first-order effects of information and communication technologies (ICT) required for private smart charging of electric vehicles (EV) in Germany. With the focus on CO_2-optimized charging, the environmental assessment compares bidirectional (V2G) and unidirectional (V1G) smart charging infrastructure to direct (uncontrolled) charging on a household level. Specifically, the applied life cycle assessment (LCA) investigates the production, transportation, operation and end-of-life phases of intelligent metering systems (iMSys) as well as private wallboxes operating with direct current (DC) and alternating current (AC). First, the technical prerequisites for smart and direct charging are outlined, with differences for direct charging depending on the household's total electricity consumption. Secondly, the LCA shows an impact of 145.4 kg CO_2-eq. per vehicle and year for V2G infrastructure by 2020, being 84 % higher than V1G (79 kg). The impact of direct charging infrastructure is significantly lower with 45.2 – 57.5 kg CO_2-eq. per year. Due to the power consumption during the operation phase, the AC and DC wallboxes contribute most with 77% (V2G) and 57% (V1G) of the impact, respectively. Assuming ongoing decarbonization of the annual average German emission factor of electricity, the total impact of private charging infrastructure can be reduced by up to 56 % (V2G) and 67 % (V1G) by 2040. Next to the high energy efficiency of components, manufacturers should focus on a sustainable design of components including longevity. Overall, the environmental impact of the ICT infrastructure for smart charging is highly dependent on the charging strategy as it determines the annual duration of charging and discharging. Suggested further research involves investigations on first-order effects associated with other smart charging strategies (e.g. peak shaving), suitable allocation methods for multifunctional ICT components (e.g. iMSys), along with an assessment of higher-order effects such as energy system-wide environmental consequences.

Keywords: Electromobility; Vehicle to Grid; Smart Charging; ICT; Life Cycle Assessment

1. Introduction

The expansion of electromobility as a sector-coupling technology is increasingly recognized as an integral part of decarbonization [1]. Studies on the integration of electric vehicles (EV) into the energy system highlight the importance of smart charging strategies from both technical and economic perspectives, including recent reports by the international agencies on energy (IEA) and renewable energy (IRENA) [2,3]. Next to unidirectional (V1G) charging, smart charging includes vehicle-to-grid (V2G) concepts, allowing to charge and discharge bidirectionally. EV batteries, thus, serve

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as flexible storage elements. The technical and economic benefits concepts as highlighted in [4-6] include peak shaving and load regulation. As a part of a smart grid, smart charging strategies are based on information and communication technology (ICT). From an environmental perspective, existing methodological frameworks on assessing ICT-based products or services (e.g. [7-9]) distinguish between first-order (direct) and higher-order (indirect) effects. While first-order effects represent the results of a life cycle assessment (LCA) on infrastructure and components, effects of higher-order include both intended benefits as well as negative side effects beyond the technology perspective as outlined in [7]. Existing environmental analyses on smart charging primarily investigate higher-order effects, with the focus being on intended benefits. In the context of smart charging, this includes simulations by [10] on V1G charging, showing a considerable reduction potential on EV's operational emissions. An analysis of V2G charging by [4] shows system-wide benefits such as grid stabilization and enhanced utilization of renewable energies (RE). An environmental assessment on V2G systems by [11] concludes an even higher reduction potential of EV operational emissions compared to V1G strategies. Especially CO_2-optimized charging strategies enable a reduction in operational emissions by shifting the charging cycle to times with a low emission factor (EMF) of electricity.

Regarding the first-order effects of private smart charging infrastructure in German distribution grids, the required ICT can be distinguished between the intelligent metering system (iMSys) components and the wallbox. With the Act on the Digitalization of the Energy Transition (GDEW), the iMSys has been legally set as the standardized communication infrastructure in German distribution systems and consists of a modern metering device (mME) and a smart meter gateway (SMGW). Concerning the wallbox, V2G charging requires power electronics for the conversion in direct current (DC), whereas wallboxes for V1G charging mostly operate with alternating current (AC). As part of an environmental impact assessment of EVs within [12], the LCA results of a small-scale wallbox are compared to those of public charging points. [13] compare the lifecycle-based impact of charging infrastructure in China, showing a comparatively higher footprint of public DC chargers compared to AC chargers. The operation phase results as the greatest contributor, notably due to the highly fossil-based electricity mix.

The overall purpose of this paper is to quantify the first-order effects of the required ICT infrastructure for smart charging strategies on a household level, including hardware components and data processing. While previous studies on first-order effects are limited to the assessment of wallboxes and other charger types, this paper investigates environmental effects of the entire ICT infrastructure, i.e. including both iMSys and wallbox components. The paper also sheds a light on the differences between required infrastructure for V1G and V2G charging compared to conventional (uncontrolled) charging, referred to as 'direct charging' in this paper. Sensitivity analyses serve to identify the most influencing parameters to derive policy recommendations for a sustainable technical design. The investigations are conducted within the research and demonstration project 'Bidirectional charging management' (BCM).

2. Method and LCI data

The scope of the comparative environmental assessment is the required infrastructure for smart charging compared to direct charging in German smart grids on a household level. The evaluation of the ICT infrastructure is based on an LCA approach and covers all lifecycle phases (production, transport, operation and end of life).

2.1. Use Case definition and system boundaries

The analyzed use case of smart charging represents private charging of an EV following an CO_2-optimized charging strategy. Among the assessed components and life cycle phases, the operation phase of the wallbox is influenced by the charging strategy and driving profile. Assumptions on the time of charging/discharging in hours per year result from simulations on the respective charging strategy by [11]. The simulation is conducted for the driving profile of an average German household with an EV battery capacity of 60 kWh. In line with the system boundaries, charging hours for private charging at home are considered while excluding any additional charging hours at public charging points.

Fig. 1 outlines the respective infrastructure for the V2G charging process. Two digital meters are required for data transfer, i.e. at the grid connection point and the wallbox. These meters are connected to the SMGW via the Local Metrological Network (LMN). The two communication protocols EEBUS and OCPP (open charge point protocol, see [14]) facilitate communication and data exchange. External market participants or electromobility service providers located in the Wide Area Network (WAN) communicate through the SMGW via the communication protocol EEBUS with the wallbox within the home area network (HAN). The backend of the mobility service provider communicates directly with the wallbox via the OCPP. Data transmission is performed via the long-term evolution (LTE) network as it fulfills the required criteria for intelligent metering as determined in [15], i.e. bidirectionality and real-time capability.

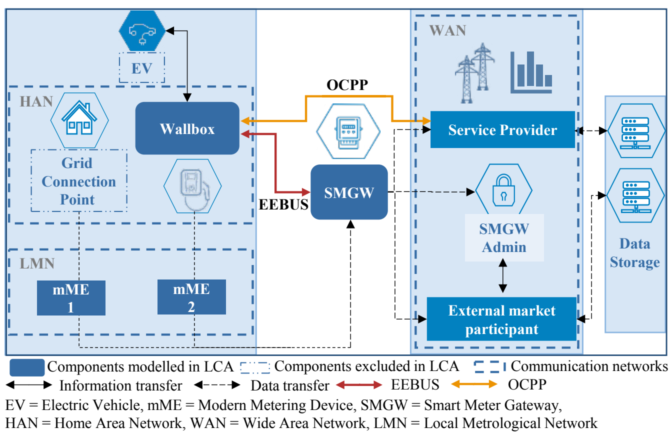


Fig. 1. ICT infrastructure and processes for V2G charging

2.2. Household scenarios

While the iMSys infrastructure is required for smart charging as outlined above, the requirements for direct charging differ depending on the specifications of the household. A mME serves as a digital electricity meter and, thus, replaces all conventional Ferraris meters in households regardless of the charging technology. The installation of a SMGW as a communication unit, however, is legally required for certain consumers only as indicated by the German Energy Industry Act (EnWG). These include either those exceeding 6,000 kWh of electricity consumption per year, owners of a RE- or combined heat and power (CHP) unit larger than 7 kW, or consumers with controllable loads for grid stabilization measures. To evaluate the additionally caused footprint of smart compared to direct charging infrastructure, this paper investigates two household scenarios for direct charging, 'MIN' and 'MID'. The scenarios are comparable to an average 1-2 person household with total annual electricity consumption, including the EV, of < 6,000 kWh (MIN) and an average 4 person household (MID) with total annual electricity consumption of > 6,000 kWh. Fig. 2 displays the differences within the infrastructure architecture for ordinary households, including those with direct charging, compared to additionally required ICT for smart charging (indicated with the dotted blue line). Table 1 outlines the resulting system boundaries for the LCA considerations.

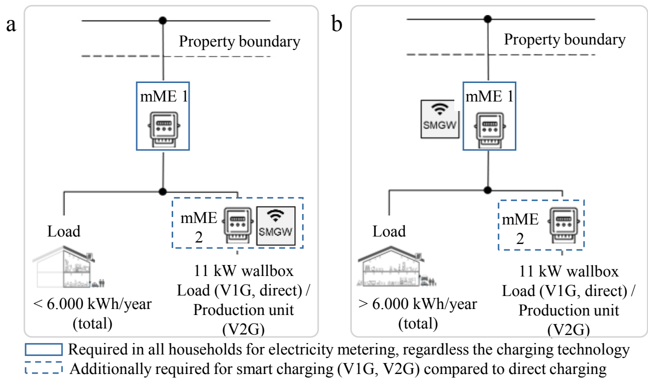


Figure 2: Infrastructure for charging in the scenarios (a) 'MIN'; (b) 'MID'

Table 1. ICT infrastructure attributable to charging per technology and scenario (x = required/ attributable to charging; o = legally required and not attributable to charging; / = not required)

	Scenario	MIN, MID	MIN	MID
	Charging technology	Smart charging (V1G, V2G)	Direct charging	
Required ICT infrastructure	mME 1	o	o	o
	mME 2	x	/	/
	SMGW	x	/	x
	iMSys data processing	x	/	x
	OCPP data processing	x	/	/
	AC wallbox	x (V1G)	x	x
	DC wallbox	x (V2G)	/	/

As a prerequisite for electricity metering, the mME 1 is excluded from the system boundaries in all scenarios. While the mME 2 and the SMGW are required for smart charging (see Fig. 1), none of the iMSys components are required for direct charging in the MIN case. The MID scenario includes the mandatory installation of the SMGW, assuming that the exceeding of the 6,000 kWh threshold is due to EV charging.

2.3. Goal and scope of LCA for first-order effects

First-order effects of the ICT infrastructure are determined through an attributional life cycle assessment (ALCA) following the ISO norms 14040:2021/14044:2006. Since the analyzed infrastructure is a prerequisite for private charging regardless of the technical parameters of the EV (e.g. battery capacity), the chosen functional unit refers to enabling the charging of a private vehicle for one year. For LCA modeling, the open source LCA software brightway2 (see [16]) is linked to the ecoinvent database (see [17]), version 3.7.1. Recycling is modeled with the cut-off allocation method and the chosen impact assessment method is "ReCiPe Midpoint (H) V 1.13 no LT". The focus of the study is on the impact category of climate change with the indicator "Global Warming Potential (GWP100)" measured in kg CO_2-eq./year. The year 2020 serves as the base year, followed by sensitivities for 2030 and 2040. The respective EMF of electricity consumed within the operation phase is based on a future scenario defined in the research project "eXtremOS" (method outlined in [18]). To include future scenarios within the background system (wider economic and technological developments within entire sectors), the superstructure approach presented in [19] is implemented into the ecoinvent database. While all life cycle phases are evaluated for hardware components, only the operational phase is considered for data transmission and storage, since these impacts are almost exclusively due to operation [20,21].

2.3.1. Inventory data on hardware

Table 2 shows the inventory data for the iMSys infrastructure and wallboxes. Next to secondary data from databases and literature, input values for hardware components are supplemented by expert interviews with manufacturers and previous analyses within the BCM project. For iMSys components, the input values are largely built upon a previous LCA on mME and SMGW by [22]. Inventory data of the wallboxes are based on supplementary material provided by [12]. For the DC wallbox, additionally required power electronics for the conversion are modeled based on ecoinvent data on "electronics production, for control units in Europe". For the remaining components, the weighting of the material composition of the AC wallbox dataset by [12], is scaled up to the weight of the DC wallbox. Table 3 displays the resulting values for the analyzed charging technologies along with the respective rated power of the AC and DC wallbox ($P_{wallbox}$) respectively. At the end-of-life, recycling rates are applied based on the European Directive 2012/19/EU on waste electrical and electronic equipment (WEEE), with 55 % for the mME and SMGW and 80 % for the wallbox [23].

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

Table 2. Inventory data of the ICT infrastructure components (data based on [22,12], expert interviews)

Parameter	mME	SMGW	Wallbox AC	Wallbox DC
Average lifetime (*years*)	12	12	15	15
Weight of components (*kg*)				
Total	2	0.2	4.6	23
Polycarbonate	0.58	0.06	-	-
Polyester	-	-	0.03	0.07
ABS	0.48	0.04	0.25	0.52
Glass fiber	0.24	0.02	-	-
Steel	0.3	-	2.8	5.9
Copper	0.07	-	-	-
Iron	0.07	-	0.01	0.03
Tin	0.07	-	-	-
Platine		0.06	-	-
Active electronic components	0.13	0.01	-	-
Passive electronic component	0.13	0.01	-	-
Liquid crystal display	0.04	-	-	-
Electronics for control units	-	-	1.2	16
Metalworking	-	-	2.8	5.9
Cable (*m*)	-	-	0.2	0.4
Polyethylene pipe (*m*)	-	-	0.07	0.15
Electricity (production) (*kWh*)	5.84	2.92	-	-

Table 3. Wallbox operating parameters for CO_2-optimized and direct charging (charging hours based on [11]; rated power in watts based on wallbox manufacturer interview)

Wallbox parameters	V2G (DC)	V1G/ direct charging (AC)
$t_{(dis-)charging}$[1,2] (*h/year*)	1,805	181
$t_{standby}$ (*h/year*)	6,955	8,579
$P_{wallbox, charging}$ (*W*)	50	20
$P_{wallbox, standby}$ (*W*)	10	10

[1] includes charging hours at home (excluding additional public charging)
[2] Slightly vary in the years 2019-2040 ([11]); for simplification, the average is chosen for calculations (base year and sensitivities)

2.3.2. Parameters for data processing

While data volumes of the iMSys infrastructure via EEBUS result from measurements published in [24], OCPP data is derived from measurements within the BCM project. The resulting volumes are displayed in Table 4 along with other assumed input values for parameters relevant for data processing. It includes the power usage effectiveness (PUE) metric for data storage efficiency (see [25]), and the power consumption of wireless transmission for the mobile access network and core network following calculations in [22]. In sum, the measured daily data volumes (D) of a few megabytes per day amount to approx. 0.96 gigabytes per year. It has to be noted that both EEBUS and OCPP data only include the required information transfer for the use case of CO_2-optimized charging while excluding other potentially required data transmissions such as firmware updates.

Table 4. Parameters for calculations on data processing (data based on [22,24,25], own measurements)

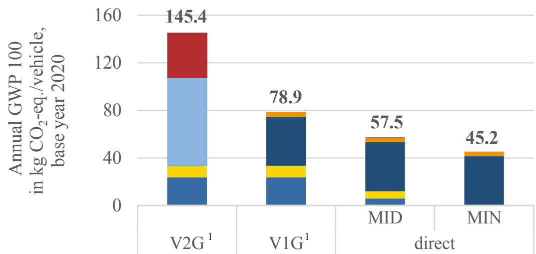
Parameter, unit	Input value
D_{EEBUS}[1] (*MB/day*)	0.73
D_{OCPP}[2] (*MB/day*)	1.89
$P_{mobile\ access\ network,\ LTE}$ (*Wh/GB*)	200
$P_{core\ network,\ LTE}$ (*Wh/GB*)	52
PUE	1.5

[1] includes regular daily operation, the standby mode of the SMGW and data transmission of the tariff application case (TAF 7) for metering data recording every 15 minutes, with transmission once per day
[2] includes messages every 15 minutes

3. First-order effects of smart charging infrastructure

3.1. Global warming potential of the base case

Fig. 3 outlines the annual global warming potential (GWP100) per charging technology resulting from the infrastructure required for private charging of one vehicle. Since the infrastructure components for smart charging are not affected by the household's electricity consumption (see Table 1), there is no distinction between MIN and MID scenarios for V2G and V1G. For direct charging, however, the difference is caused by the additionally required SMGW in the MID scenario. First, the differences between V1G and V2G are investigated. With 145.4 kg CO_2-eq. per vehicle, Fig. 3 shows that the annual GWP of V2G charging infrastructure is 84 % higher compared to V1G charging. As there are equal requirements for V2G and V1G regarding the iMSys components, the difference is caused by the higher footprint of the DC wallbox compared to the AC wallbox. This is due to the additional power electronics in the production phase and the longer operating times, including discharge hours. Effects due to data processing (transmission and storage) are included in the operation phase of the iMSys but are marginal for both V1G and V2G (< 0.2 % of total impact). Secondly, the additional climate impact of smart charging infrastructure compared to direct charging is evaluated. In the MIN scenario, the impact of direct charging is 69 % lower compared to V2G charging. The gap to smart charging is decreasing for households already exceeding an



	V2G[1]	V1G[1]	direct MID	direct MIN
other (transport, eoL)	0.3	0.3	0.3	
AC wallbox production		3.9	3.9	3.9
AC wallbox operation		41.3	41.3	41.3
DC wallbox production	37.8			
DC wallbox operation	73.8			
iMSys components production	9.7	9.7	6.1	
iMSys components operation	23.7	23.7	5.9	

[1] Required infrastructure for smart charging equal in MIN and MID scenarios

Fig. 3. LCA results (GWP 100) for the required infrastructure for smart charging in kg CO_2-eq. per vehicle and year for the base year 2020

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

annual electricity consumption of 6,000 kWh, with the impact of V2G charging being 60 % lower compared to the MID scenario.

To evaluate the magnitude of first-order effects, the LCA results are compared to the achievable reduction of EV's operational emissions through CO_2-optimized charging, as determined within the BCM project (see [11]). In 2019, results show EV operational emissions of 1,167 kg CO_2-eq. for direct charging, 909 kg CO_2-eq. for V1G, and 219 kg CO_2-eq. for V2G charging. By 2030, there is a reduction potential of up to 60 % in the case of direct charging, even leading to emission savings (-548 kg CO_2-eq.) in the case of V2G. This results from shifting the point of time of the charging/discharging processes, where CO_2-optimized charging strategies lead to charging in times of low EMF and discharging in times of higher EMF. It has to be noted that presented values on operational emissions include both private and public charging processes. Despite the different system boundaries compared to the analysis of first-order effects, the results show an overall environmental benefit of V2G charging. The reduction potential within the operational emissions of EVs exceeds the first-order effects by a multiple. Simulations of CO_2-optimized charging strategies, however, also show a significant increase in peak loads and EV full cycles that poses an additional strain on electricity grids and operating assets. The environmental impact of these side-effects needs to be investigated as higher-order effects of smart charging in further research.

3.2. Sensitivity analyses on lifetime and operating efficiency

Sensitivity analyses are conducted for parameters that influence the operation and production phases of the hardware components under investigation (see Table 5). The first sensitivity analysis investigates the influence of ongoing decarbonization of electricity production in Germany. While for the base year 2020 the EMF is assumed with 462 g CO_2-eq./kWh, the LCA is modeled with a decreasing EMF of 194.5 and 98.9 g CO_2-eq./kWh for the years 2030 and 2040. Fig. 4 shows the resulting reduction of the impact for all charging technologies. Depending on the share of the operation phases in the total footprint, the potential ranges from a 56% reduction (V2G) to 72% (direct charging, MIN). This sensitivity is conducted for the base configuration, i.e. average energy efficiency and lifetime of components as indicated in Table 5. Further sensitivities investigate the potential contribution of improved energy efficiency and longevity of components on the example of the V2G charging infrastructure.

Table 5. Lifetime ($t_{lifetime}$) and electricity consumption (E_{el}) of components for the base case and sensitivity analyses (data based on [22], expert interviews)

Component parameters	mME	SMGW	Wallbox AC	Wallbox DC
$t_{lifetime,\ base\ case}$ (*years*)	12	12	15	15
$t_{lifetime,\ sensitivities}$ (*years*)	8 – 20	8 – 20	10 – 20	10 – 20
$E_{el,\ base\ case}$ (*kWh/ year*)	12.3	38.5	89	161
$E_{el,\ sensitivities}$ (*kWh/ year*)	7.0 – 17.5	29.8 – 47.3	62.4 – 124.1	131.3 – 198.1

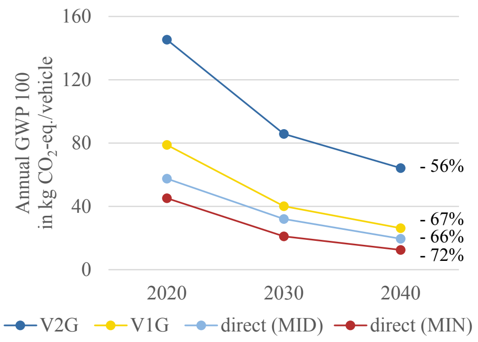


Fig. 4. Sensitivity of LCA results (GWP 100) of charging infrastructure in kg CO_2-eq. per vehicle and year with decreasing EMF of electricity, all scenarios

While results show a slightly greater reduction potential for higher energy efficiency in the base year 2020, longer lifetimes show a comparatively greater GWP reduction potential in the future of up to -39 % by 2040. This is due to the ongoing decarbonization of the EMF and thus, the higher relevance of the production phase compared to the operation.

3.3. Limitations of the analyses

This study investigates the first-order effects of private charging infrastructure for CO_2-optimized charging as a use case. First and foremost, the wallbox's operation phase determines the greenhouse gas (GHG) emissions as the life-cycle phase with the most significant impact. The operating hours in this study result from simulations on the use case of CO_2-optimized charging with the driving profile of an average German household and a battery capacity of 60 kWh. When analyzing other driving or EV specifications, the charging/discharging hours need to be adjusted accordingly. Also, future business models might require a significantly higher data transfer resolution compared to CO_2-optimized charging, e.g. per minute or even higher. For further research, it is suggested to analyze other use-cases of smart charging, e.g. peak shaving, to determine the associated environmental impact. Secondly, the system boundaries are limited to private charging infrastructure and respective charging hours. Public charging and associated infrastructure are not considered and require further analysis. Thirdly, in this LCA the respective iMSys components are entirely allocated to the EV charging infrastructure. Since these devices might most likely serve for other purposes, e.g. metering or control of other loads/production units, the multifunctionality needs to be addressed with the development of a suitable allocation method in further LCA studies. Lastly, the analysis is conducted for the German requirements of ICT infrastructure including requirements for iMSys infrastructure. An environmental assessment of charging infrastructure in other countries requires an analysis of national requirements and respective adjustments of system boundaries.

4. Conclusion and Outlook

This study analyzes the first-order effects attributable to the required ICT infrastructure for CO_2-optimized smart charging in Germany, including iMSys and wallbox components, compared to direct charging. Next to LCA results, the study provides a technical overview of the required ICT infrastructure depending on the charging technology. Compared to direct charging infrastructure, LCA results show an overall higher annual footprint per vehicle of up to 145.4 kg CO_2-eq. for V2G and 79 kg CO_2-eq. for V1G charging infrastructure, respectively. The footprint of direct charging infrastructure is between 27 % – 69 % lower compared to V2G and V1G charging, depending on whether the SMGW is already required for direct charging. Overall, the operation and production phases of the AC and DC wallbox contribute with the greatest share to the GWP. Resulting from the high impact of the operation phase, sensitivity analyses show that the ongoing decarbonization of the electricity production drastically decreases the impact in the future. Consequently, the production phase becomes more relevant and, thus, manufacturers should focus on a sustainable technical design including longevity of components. Compared to the achievable reduction of EV operational GHG emissions from 1,167 kg CO_2-eq. for direct charging to 219 kg CO_2-eq. for CO_2-optimized V2G charging, results show that the first-order effects can be compensated by a multiple. Determination of first-order effects of use cases other than CO_2-optimized charging along with potentially positive or negative higher-order effects are excluded from the assessment and are subject to further research. For a holistic assessment of environmental higher-order effects including systemic consequences within the energy system (e.g. RE-integration, grid stabilization), the coupling of energy system modeling with an LCA approach is proposed.

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Environmental effects of vehicle-to-grid charging in future energy systems – A prospective life cycle assessment

Daniela Wohlschlager [a,b,*], Stephan Kigle [b,c], Vanessa Schindler [d], Anika Neitz-Regett [b], Magnus Fröhling [a]

[a] Professorship Circular Economy, Technical University of Munich (TUM), Campus Straubing, Am Essigberg 3, 94315 Straubing, Germany
[b] Forschungsstelle für Energiewirtschaft (FfE), Am Blütenanger 71, 80995 München, Germany
[c] School of Engineering and Design, Technical University of Munich (TUM), Arcisstraße 21, 80333 München, Germany
[d] Institute for Resource Efficiency and Energy Strategies (IREES), Durlacher Allee 77, 76131 Karlsruhe

HIGHLIGHTS

- Vehicle-to-grid (V2G) accelerates the integration of fluctuating renewable energies
- In the medium-term, V2G reduces systemic emissions and electric vehicle impacts
- From 2040 onwards, the effects on emissions decrease from both perspectives
- BEV batteries as systemic storage options substitute 117 GWh of stationary batteries

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ABSTRACT

Vehicle-to-grid (V2G) is increasingly recognized as a concept that uses battery electric vehicles (BEVs) as flexible storage options, enabling both charging and discharging of vehicle batteries. Applications of V2G aim towards technical and economic benefits from the system and end-user perspectives. Life Cycle Assessments (LCA) on BEVs indicate that charging strategies potentially reduce operational emissions. Besides evaluating environmental effects on the 'technology level', the literature recommends considering impacts on the 'system level' caused by a diffusion of the investigated technology. Since the future electricity mix per hour of (dis)charging is decisive for the impact of BEVs, systemic effects include repercussions of charging strategies on hourly electricity generation. When analyzing future scenarios, a prospective LCA (pLCA) allows us to consider technological developments. To assess the impact of charging strategies, the literature lacks a consistent framework that applies a pLCA approach and considers repercussions on the hourly greenhouse gas (GHG) emissions of electricity. The contribution of this article is the consolidation of the system and technology point of view when assessing V2G services. First, we present a framework that combines energy system modeling and a comparative pLCA to assess medium and long-term effects. To prove its suitability, the framework is exemplarily applied to evaluate two cost-minimized climate policy scenarios of Germany, i.e., with and without the option of V2G charging. The article outlines repercussions on the electricity system from 2025 to 2045 in an hourly resolution. This allows determining the impact per charging strategy on the technology level compared to conventional passenger cars in the second part of the study. Despite the insignificant effects on total GHG emissions by 2045, V2G charging accelerates decarbonizing electricity generation in the medium-term (2030–2035). When assessing the impact on BEVs, V2G causes substantial reductions. By 2030, operational emissions decrease between −50% and almost −200% compared to uncontrolled charging (144 kgCO_2e/BEV). These potentials depend on the allocation of GHG savings reached through the secondary purpose of BEVs, i.e., a storage option for the energy system. With the ongoing decarbonization of electricity, however, the potential of V2G to reduce operational GHG emissions decreases, and the production phase gains importance. Regarding long-term contributions, substituting 117 GWh of stationary batteries indicates a reduction in raw material demands. Overall, combining the system and technology levels in a prospective assessment enhances the understanding of environmental effects caused by a

* Corresponding author at: Professorship Circular Economy, Technical University of Munich (TUM), Campus Straubing, Am Essigberg 3, 94315 Straubing, Germany
E-mail address: daniela.wohlschlager@tum.de (D. Wohlschlager).

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large-scale diffusion of V2G charging. Researchers can further apply the outlined method for assessing use cases in other geographical scopes and time frames.

1. Introduction

The European Union defined the goal of reaching climate neutrality by 2050, i.e., aiming at a 100% reduction of greenhouse gas (GHG) emissions compared to 1990 levels [22]. Some European countries have even committed to stricter targets, including Germany with the national goal of reaching climate neutrality by 2045 [14]. Thus, electricity supply in many countries is expected to be dominated by renewable energies (RE) from wind turbines and decentralized generation units, e.g., photovoltaic (PV). Studies highlight the relevance of storage technologies for successfully integrating fluctuating electricity generation from RE. Besides seasonal storage options, a review by Datta et al. [16] highlights the provision of flexibility from battery energy storage systems (BESS) as short-term storage options. Accordingly, the functions of BESS to integrate RE include a fast provision of electricity and the option for peak-shaving. Besides the expansion of RE, technological development and decarbonization strategies in the consumption sectors result in ongoing electrification [47]. Batteries are, therefore, also increasingly deployed in the transportation sector by switching from vehicles with internal combustion engines (ICEVs) to battery electric vehicles (BEVs). Legislation in the EU fosters these developments. By 2035, the sale of new ICEVs will be banned [23]. For an efficient integration of BEVs into the energy system, developments towards innovative charging strategies have increased. While smart unidirectional charging (V1G) optimizes the charging process following one or several objectives [35], BEVs still represent a load for the energy system. Bidirectional or Vehicle-to-Grid (V2G) charging, however, allows using vehicle batteries as flexible storage options. As outlined in a review by Sovacool et al. [64], the concept was first introduced by Kempton and Letendre [41] as *"a two-way, computer-controlled connection to the electric grid. That is, the grid could receive power from the vehicle as well as provide power to the vehicle."* Depending on the optimization strategy, a variety of use cases are currently investigated: As outlined by Englberger et al. [20], V2G concepts offer flexibility for the energy system through the provision of grid services, i.e., peak shaving and frequency containment reserve. While V2G allows to feed electricity back into the grid, vehicle-to-home (V2H) enables the supply of a house with electricity as discharged from the BEVs. [9] Applications of V2H include optimizing the self-consumption of local RE generation, typically from PV. [15,27] From the end-user perspective, studies further emphasize combining these charging strategies to maximize the revenue potential [42]. Concerning environmental impacts, studies on assessing charging strategies found an overall GHG reduction over the life-cycle of BEVs by shifting charging hours into times of low carbon electricity generation, i.e., hours with a high share of RE and feeding back in times of low RE availability (e.g., [13,33,77]). Following previous definitions, we refer to the function of bidirectional charging when using the terms 'V2G' or 'V2H' in this article, i.e., the function of both charging and discharging of BEVs.

Use cases of charging strategies require information and communication technologies (ICT) as part of the transformation towards 'smart energy systems' (SES) (cf. [49]). To assess the environmental impact of ICT-enabled use cases, existing methodological frameworks distinguish between environmental effects on different levels – the 'technology,' 'user,' and 'system level' [57]. Effects on the technology level comprise the life-cycle-based footprint of components (e.g., ICT infrastructure, BEV), typically quantified through a Life Cycle Assessment (LCA). Behavioral changes cause effects on the user level. This effect has been investigated extensively for the example of smart charging, indicating that driving and charging behavior highly impacts the flexibility potential of BEVs [35] and, thus, the environmental performance [75]. Effects on the system level result from large-scale adoption of the investigated product or services. Dimensions of systemic effects of ICT differ in the literature, including structural changes within society or economy-wide consequences [57]. Wohlschlager et al. [73] investigated these different environmental effects concerning emerging use cases in SES. In their definition, effects on the system level concern repercussions within the energy system. A ranking of potential impacts shows that effects on the system level contribute the most to the overall LCA results. At the same time, the authors conclude that determining systemic effects poses high challenges that require additional methods beyond the standardized LCA methodology. Recommendations include conducting a consequential LCA (CLCA) when assessing currently novel technologies or products in future SES scenarios. A CLCA considers changes ('consequences') due to decision-making within the system in which the investigated product or technology emerges [38].

In energy system analysis, such systemic consequences within future scenarios are typically determined using an energy system model (ESM). Through simulation or optimization techniques, an ESM depicts the energy system with all energy carriers for a given year, such as electricity, natural gas, and hydrogen, and analyzes system compositions. ESMs have been widely applied to model and assess climate mitigation scenarios (e.g., [10,53]). These scenarios include a reduction target of emissions, e.g., to achieve climate goals [69]. Considered emissions mainly include those caused during the operation phase (e.g., combustion of fossil fuels) while excluding upstream emissions (e.g., manufacturing and downstream of technologies). Since the impact of electricity generation in an increasingly RE-based energy system shifts from the operation to the manufacturing phase, the consideration of life-cycle impacts gains importance [10,53]. By 2011, the Intergovernmental Panel on Climate Change (IPCC) had already highlighted the consideration of LCA when using existing ESM as an enormous advantage for future research [19]. Later, Guinée et al. [30] named the application of ESM when assessing systemic effects as a separate discipline within the field of LCA.

Methodological approaches to include an LCA when defining and assessing scenarios from an ESM have been continuously developed and applied over the last years. A review by Blanco et al. [10] identifies different approaches, which can be distinguished between ex-post assessments and endogenous consideration of LCA indicators. In ex-post assessments, the ESM excludes any environmental impact categories in the objective function. The ESM can follow other optimization criteria (e.g., costs) or a simulation approach. An LCA is performed after the model run, i.e., on the results of modeled scenarios [10]. In contrast, an endogenous consideration includes one or several LCA indicators in ESM optimization. It can be conducted through multi-objective optimization [4] or monetization of externalities [28]. Lastly, multi-attribute decision-making (MADM) approaches serve to find an optimal solution among different alternatives or scenarios, such as those outlined and applied by Hottenroth et al. [34].

One overarching challenge across these different methodological approaches is adequate consideration of future developments within the LCA. To study the environmental impact of currently emerging technologies (i.e., in an early stage of development) in the future, the approach of a 'prospective LCA' (pLCA) has been developed and defined by [5]. As outlined in Fröhling and Hiete [26], a pLCA approach is not congruent with a CLCA, which can also be retrospective and thus feasible to investigate existing products or technologies. A pLCA requires the consideration of future developments in both the fore- and background systems [65]. While the foreground in an LCA determines specifications of the investigated technology, e.g., lifetime, efficiency, or size of a wind turbine, the background concerns changes within the economic system of the future, e.g., affecting processes and emissions along the global supply chain to produce the turbine. Literature on environmental assessments of future energy systems shows challenges when adjusting the background as it involves an extensive modification of the Life Cycle Inventories (LCI) [40,54,58]. Wohlschlager et al. [73] outline that LCI databases (e.g., Ecoinvent) not only contain data on the status quo but often even outdated information. Several working groups have developed pLCI databases for a systematic transformation [65].

Previous LCAs on BEVs conclude on a higher production-based impact than ICEVs due to the GHG-intense battery production. In contrast, overall life-cycle impacts can be reduced during the operation phase [13,17,45]. Regarding energy system-wide effects specifically caused by different charging strategies, few analyses applied a pLCA in combination with a consequential approach using an ESM. Knobloch et al. [45] and Sacchi et al. [60] combine ESM and pLCA to assess BEVs but exclude investigating charging strategies. Arvesen et al. [6] investigate unidirectional charging but excluded the option of V2G charging. Xu et al. [76] investigate the effects of both V1G and V2G charging on European electricity production but exclude an investigation of repercussions on required alternative storage technologies (e.g., first or second-life BESS) in the scenarios. Tackling this issue, Zhao and Baker [79] assess the life-cycle impact of electricity when using first- and second-life stationary BESS compared to V2G. The study, however, neither considers a prospective approach for determining the emission factors of electricity generation nor any system-wide repercussions, e.g., on total electricity generation and consumption.

To summarize, it is necessary to consider how BEV batteries as storage options will influence the electricity generation in the first place before assessing the technological impact of BEVs operating in such a future system. The current research lacks a framework that incorporates a prospective and consequential LCA approach to determine the systemic consequences of V2G charging compared to alternatives, e.g., stationary BESS. Such a framework needs to determine respective future GHG emissions in an hourly resolution, serving as an input to quantify operational emissions of BEVs. The interplay between consequences within the system and its effects on the technological impact of BEVs thus needs consideration for a holistic impact assessment of V2G charging caused in the coming years.

Building upon these research gaps, this article elaborates on the overarching question:

What are the prospective life-cycle impacts of V2G charging on GHG emissions when considering the repercussions within the future electricity system and its consequences on the operation of BEVs?

To answer this, the analysis is structured upon two research questions to determine the effects on the system and technology levels:

1. How does a diffusion of V2G charging and, thus, the availability of BEVs as flexible storage options impact the electricity system and associated life-cycle GHG emissions of electricity generation?
2. How do systemic consequences on electricity generation impact the operational life-cycle GHG emissions of BEVs and the environmental break-even with ICEVs, depending on the charging strategy?

To answer the first research question, we develop a method that combines an ESM with a pLCA approach. Applied to the case study of Germany, the article proves the method's suitability on the example of assessing cost-optimized V2G charging compared to V1G and uncontrolled charging. Results provide pLCA-based emission factors in an hourly resolution for the time frame 2025–2045. Used as an input for the second research question, this work integrates the effects on the system level when evaluating the technologies' future impact. Determining the respective 'environmental break-even' serves as a comparison with ICEVs. It indicates the time frame of BEV's operation where the cumulative impact reductions during the operation phase compensate for the higher footprint of the production phase.

Overall, this work enhances the understanding of potential environmental effects associated with a diffusion of V2G charging in the medium and long-term. The novelty with respect to current literature resides in the adopted prospective LCA approach and in consolidating impacts from the system and technology point of view. As a methodological contribution, the article outlines a consistent set-up to investigate the effects on both levels. For evaluating the impact on BEVs in the case of smart charging, the article includes methodological guidance by reflecting upon two approaches for allocating impacts resulting from the secondary purpose of providing flexibility for the system. Results of the case study provide insights for industry and political decision-makers on the medium- and long-term effects of V2G charging. Researchers can further transfer the outlined method to assess emerging use cases in other geographical scopes and time frames.

The article comprises six sections. Section 2 provides a literature review on studies that apply an LCA to future energy system scenarios, including those explicitly focusing on BEVs. Section 3 outlines the methodological steps for assessing the two research questions, i.e., the effects on the system and technology levels. Section 4 outlines the resulting climate impact of German electricity generation in the 'V2G' and 'Reference' scenarios (system level). This is followed by results on the effects per BEV and the environmental break-even with ICEVs (technology level). The article closes with a discussion of the results and a critical reflection on the limitations of this study.

2. Literature review – LCA in energy system modeling

Table 1 presents relevant literature on applying LCA in combination with an ESM. The overview distinguishes between three types of investigations depending on the focus of the study, i.e., development of methodological frameworks to link an ESM and LCA [D], impact assessments of scenarios or technologies [U], or focusing on both describing a methodology and the subsequent application of the framework [D/U]. The table includes information on the approach for combining the methods of LCA and ESM, i.e., ex-post assessment [EX] or endogenous consideration [EN].

Six reviewed studies focus on developing a methodological framework [D]. The approaches include both ex-post assessments and an endogenous consideration. Some studies developed and applied tools for a systemic modification of the background system to create pLCI databases, such as *THEMIS* [5,48,55], *Wurst* [58,69], *FRITS* [34,39,53,54]. The most recent development is the premise framework [61], providing pLCI databases using data from Integrated Assessment Models (IAMs) and literature. IAMs are widely accepted global models that include scenarios based on shared socioeconomic pathways (SSPs) [59]. Junne et al. [40] argue that global models such as IAMs should be preferred to adjust background processes compared to regional changes, e.g., on a European level, when assessing electricity generation technologies since these are manufactured globally. Other studies in Table 1 partly apply an adaptation of the background system using different methods, i.e., without mentioning using one of these previously developed tools/methods.

The majority of analyzed studies investigate climate change mitigation scenarios [CS]. Several articles assess scenarios from IAMs, while others apply ESMs reaching from global to regional scopes. Some use existing models with predefined scenarios, e.g., the global IEA scenarios [37] investigated by Pehl et al. [55], while others define their scenarios. Studies frequently model scenarios with a reduction target of −80% and − 95% of GHG emissions (compared to 1990-levels) on a global [40,71], European [10,39], or national level [53,54]. Similarly, Arvesen et al. [5] model scenarios with the target of limiting global warming to 2 °C. With some exceptions, the investigated time frame of most studies reaches until the year 2050.

The ex-post assessment on climate mitigation scenarios by Luderer et al. [48] provides a detailed analysis regarding the environmental performance of the electricity mix' modeled in the IAM scenarios. In the example of Canada's energy system, Fernández Astudillo et al. [25] show that using electrification rather than combustion technologies

Table 1
Literature review on studies combining LCA with energy system modeling.

Study	Geographical scope	Time horizon	Assessed system	The focus of the study	Approach of ESM and LCA combination	Using IAM as ESM (yes/no)	pLCI background adaptation (yes/no)	Background database adaptation method	Scenario scope
Volkart et al. [71]	Global, Regional	2010–2060	Energy system	D	EN	n	n	–	CS
Al Shidhani et al. [4]	National or regional possible	2016–2030	Electricity system	D	EN	n	n	–	CS
Volkart et al. [71]	Global, Regional	2010–2060	Energy system	D	EN	n	n	–	CS
Tokimatsu et al. [67]	Global	2010–2150	Energy & biomass, and mineral resources	D	EN	y	n	–	CS
Xu et al. [76]	Europe	2050	Electricity system, focus on flexibility options	D	EN	n	Partly*	Learning curve approach and literature	CS
Mendoza Beltran et al. [51]	Global	2050	Electricity market shares, plat performance change of fossil, nuclear, biomass, adding carbon capture and storage	D	EX	y	y	Wurst	CS
Arvesen et al. [5]	Global	2010, 2030, 2050	Electricity system	D/U	EN	y	y	THEMIS	CS
Fernández Astudillo et al. [25]	National, Regional (Quebec, Canada)	1990, 2030, 2050	Transport, electricity & industry	D/U	EX	n	n	–	CS
Blanco et al. [10]	EU	2050	Energy system, focus on Power-to-methane	D/U	EX	n	y	Complementary databases literature	CS
Junne et al. [40]	Global	2015–2050	Energy and transportation technologies	D/U	EX	n	y	FRITS	CS
Naegler et al. [54]	National (Germany)	2021–2050	Energy & transport technologies	D/U	EN	n	y	FRITS	CS
Sacchi et al. [61]	Global	2005–2100	Electricity generation, transport, fuels, steel production, cement production	D/U	EN	y	y	Premise	CS
Pehl et al. [55]	Global	2010, 2030, 2050	Energy & major industry processes	U	EN	y	y	THEMIS	CS
García-Gusano et al. [28]	National (Spain)	2015–2050	Electricity system	U	EN	n	n	–	CS
Luderer et al. [48]	Global	2010, 2050	Electricity system	U	EX	y	y	THEMIS	CS
Vandepaer et al. [69]	National (Switzerland)	2010–2050	Energy system	U	EN	n	y	Wurst	CS
Naegler et al. [53]	National (Germany)	2050	Energy & transport technologies	U	EX	n	y	FRITS	CS
Junne et al. [39]	Europe, Regional	2050	Energy & transport technologies	U	EN	n	y	FRITS	CS
Reinert et al. [58]	National (Germany)	2016 & 2050	Electricity system	U	EN	n	y	Wurst	CS
Hottenroth et al. [34]	National (Germany)	2021–2050	Energy & transport technologies	U	EN	n	y	FRITS	CS
Knobloch et al. [45]	Global	until 2050	Electricity system, focus on BEVs & heat pumps	U	EX	y	Partly*	Literature	Tech
Xu et al. [76]	Europe	2015, 2050	Electricity system, focus on BEV charging strategies	U	EX	n	Partly*	Learning curve approach and literature	Tech
Arvesen et al. [6]	Europe	2050	Electricity system, focus on BEV charging strategies	U	EX	y	y	THEMIS	Tech
Sacchi et al. [60]	Global	2020–2050	Electricity system, focus on BEVs	D/U	EN	y	y	Premise	Tech

* no mentioning of specific tool/database for systematical adjustment of the background LCI database; Legend: D… development of a pLCA framework, U… using existing framework; EN… endogenous, EX… ex-post; n… no; y… yes; CS… climate change mitigation scenarios, Tech… technology specific scenarios.

reduces environmental impacts significantly. Junne et al. [40] apply *FRITS* to analyze Germany's energy system using background adaptations and find that resource consumption and land use will increase in the future system due to biomass and road passenger transport. *FRITS* is further applied by Naegler et al. [54] to assess different transformation strategies for Germany. The authors highlight that very intensive climate mitigation strategies result in a slightly better environmental performance than medium-intensive strategies. The study proposes electrification of heat and transport, renewable electricity generation, and less and more environmentally friendly cars.

Endogenously considering LCA indicators through a multi-objective optimization, Al Shidhani et al. [4] conclude that an optimization towards minimizing emissions and the least social opposition results in mainly RE-based production. In contrast, minimizing land use produces a higher share of fossil-based electricity generation. In a multi-objective optimization for the European and North African power systems, Junne et al. [39] show a substantial shift of generation technologies when optimizing by LCA-based emissions compared to the cost-minimized scenario, e.g., a higher share of wind offshore in the emission-optimized vs. more PV in the cost-minimized scenario. In a multi-objective optimization for the Swiss energy system, Vandepaer et al. [69] conclude that a slight increase in costs (+ 5%) compared to the optimal solution can result in outcomes close to the most environmentally friendly pathway.

Resulting values per impact category cannot be compared directly between existing studies due to varying goal and scope definitions, modeling strategies, and underlying data. Nevertheless, they all focus on decarbonizing and mitigating climate change. Investigated studies agree on the overall reduction of most impacts when decarbonizing the energy system and on increased impacts related to land use. Additionally, Tokimatsu et al. [67] as well as Naegler et al. [53] predict an increase in the values of impact categories on minerals, Vandepaer et al. [69] related to metals, Volkart et al. [71], as well as Junne et al. [39] related to water. Junne et al. [39] also discovered that ionizing radiation will increase due to nuclear electricity generation. Naegler et al. [53] and Vandepaer et al. [69] state that human health indicators might increase when the energy system is decarbonized.

As indicated with [Tech] in the scenario scope, the lower part of Table 1 outlines assessments specifically focusing on BEVs. Knobloch et al. [45] conduct an ex-post assessment on electrification measures, including replacing ICEVs with BEVs. Sacchi et al. [60] apply the *premise* framework to conduct a pLCA on BEVs compared to vehicles fueled by fossil or synthetic gasoline, using a baseline and a climate policy scenario from an IAM. With a global focus, the study introduced the Python library '*carculator*', enabling a pLCA-based assessment of future passenger cars. However, both studies exclude evaluating different charging strategies and their respective impacts. In an ex-post evaluation, Arvesen et al. [6] investigate the effect of unidirectional charging using a pLCA approach for two climate policy scenarios on a European level. The authors conclude that day charging is favorable regarding emissions compared to charging during the night or uncontrolled charging. Besides shifting charging times into certain hours of the day rather than modeling the charging profiles based on price signals, the study further differs from our approach by excluding the option of V2G charging. Filling this gap, Xu et al. [76] consider V2G charging compared to uncontrolled or unidirectional (V1G) charging in scenarios in the European electricity sector. The authors conduct an ex-post assessment using a cost-optimized ESM. While the study investigates different charging strategies, it excludes a comparative investigation of the deployment of alternative storage technologies (e.g., first or second-life BESS). Also, Xu et al. [76] determine implications for total GHG emissions and the annual average electricity mix while excluding the provision of hourly GHG intensities required to evaluate the impact of BEVs per charging strategy.

Overall, the reviewed literature shows different methods to determine systemic repercussions of emerging technologies within future scenarios from a life-cycle perspective. While endogenous approaches with multiple objective functions serve to evaluate trade-offs between costs, environmental impacts, or even social dimensions, ex-post assessments are typically applied for a comparative impact assessment of different scenarios modeled in an ESM. The model complexity can be reduced through ex-post studies, and uncertainties regarding monetization or weighting between objectives are avoided [10]. With the focus on assessing the systemic consequences of V2G as an emerging technology, we apply an ex-post assessment. By choosing a scenario design with and without considering BEVs as flexible storage options, this article allows a consequential analysis of the systemic effects of V2G charging. Reviewed studies explicitly assessing the impact of charging strategies insufficiently investigate the interplay between systemic repercussions and the consequences of the technologies' impact. This includes providing hourly GHG emissions of electricity, which is required to conclude on the impact of BEVs operating in such a future system. Building upon these research gaps, we enhance the investigation of systemic effects from a pLCA perspective and combine it with evaluating the impact of V2G charging on BEVs. This article allows a combined investigation of both perspectives by applying a consistent methodological set-up for assessing the system and technology levels, e.g., equal underlying scenarios and pLCA approach. The following section outlines the details of the assessment.

3. Methods

Fig. 1 outlines the methodological framework to evaluate the life-cycle impacts of V2G charging from the perspectives of both the system and technology levels. As V2G represents a currently emerging technology, our study applies a pLCA approach, using scenario modeling and the *premise* framework. Conducting an ex-post assessment, we determine systemic repercussions using a cost-optimized ESM (Section 3.1.1). For the case study on the German electricity sector, we evaluate the effects of V2G charging for two scenarios, i.e., with and without using BEVs as flexible storage options (Section 3.1.2). For both perspectives, this section outlines the four steps of an LCA as defined in the ISO norms 14,040:2021/14044:2006, i.e., goal and scope definition (Section 3.1), the inventory analysis, impact assessment (Section 3.2), and interpretation (Section 3.3).

3.1. Goal and scope definition

As outlined in Section 1, the scope of the analysis encompasses the environmental impact of utilizing BEVs as flexible storage options on the system and technology levels. In line with previous studies on the systemic effects of BEVs (e.g., Knobloch et al. [45], Xu et al. [76]) and due to the relevance of the environmental break-even of BEVs on the technology level, we investigate the impact category of 'climate change' and determine the differences of the life-cycle GHG emissions. Besides direct (combustion-based) GHG emissions, the values thus include the impact resulting from the upstream chain, e.g., the production phase of wind power plants. The '100-year Global Warming Potential' (GWP100a) indicates the impacts of released emissions over 100 years. The IPCC typically provides characterization factors for the GWP100a [38]. Thus, we choose 'IPCC 2013 no LT' (no LT = no long-term emissions) as an impact assessment method.

3.1.1. Applied energy system model

As described by Kigle et al. [44], 'ISAaR' is an European, linear optimization multi-ESM, minimizing the total system's costs considering multiple energy carriers. Modeling horizons are performed in five-year steps with an hourly resolution per year. Information on unit expansion is shared between consecutive simulation years to guarantee a continuous evolution of the energy system on the way to climate neutrality. The time horizon in 'ISAaR' ranges from 2025 to 2050, and the spatial extent includes the EU27 plus Norway, Switzerland, and the United Kingdom. Böing and Regett [12] outline the model landscape, which consists of the supply and consumption of the following energy carriers: electricity, district heating, hydrogen, liquid hydrocarbons, gaseous hydrocarbons, and biomass. An energy balance is modeled for each energy carrier. The final energy demand from the energy consumption sectors industry, transport, and buildings defines the minimum requirements for the energy system. In addition to GHG ceilings limiting the total amount of direct (combustion-based) GHG emissions per year, the demand serves as a boundary condition for the optimization. The ESM thus balances energy demand and supply per energy carrier in each optimization step. To do so, 'ISAaR' optimizes the dispatch and expansion of all energy system elements with their

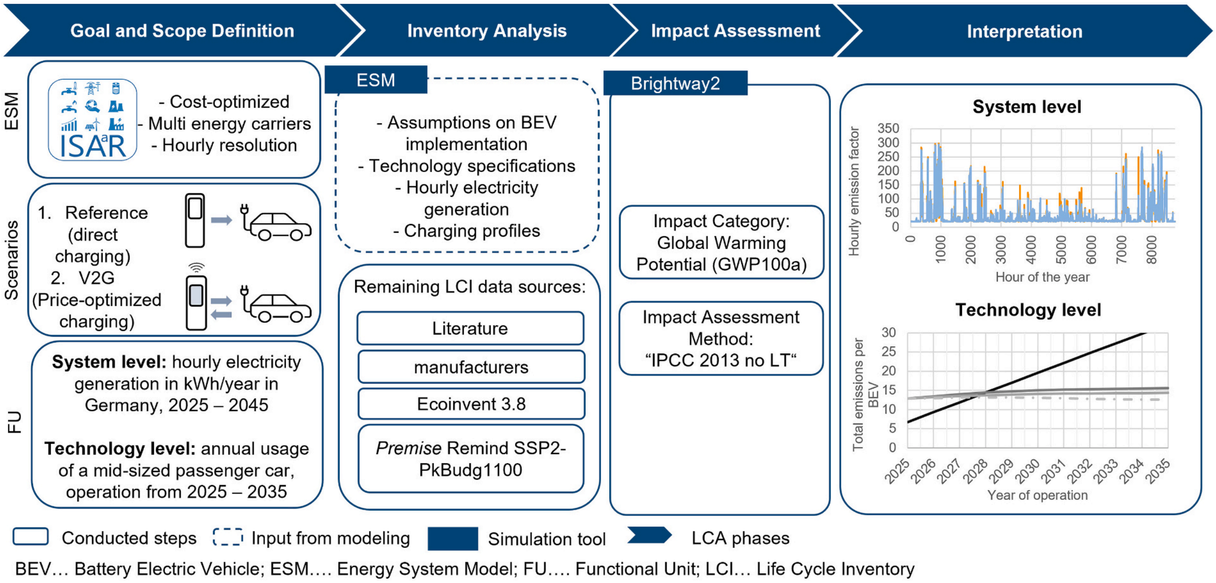

Fig. 1. Overview of the methodological framework for the comparative pLCA.

respective operating and investment costs. This includes the conventional power plant fleet, the energy production from renewables depending on the respective generation potentials, and flexible consumption technologies such as electrolysis or large-scale heat pumps.

To apply our methodological framework, we use 'ISAaR' to model the future electricity sector for the case study of Germany. Although the national scope of the analysis, consequences caused by changes in the European electricity system are considered since 'ISAaR' models the German electricity sector in the context of the European electricity market. In line with the five-year time steps modeled with 'ISAaR,' we investigate the changes from 2025 until 2045, i.e., the year Germany set its goal for reaching climate neutrality [14].

3.1.2. Scenarios

The basis for the 'V2G' and 'Reference' scenarios is the updated version of the 'solidEU' scenario. As described by Kigle et al. [44], 'solidEU' represents a climate protection scenario assuming increased cooperation within Europe to achieve the climate targets. We build upon this scenario as it consistently describes the socio-political context leading to deep GHG emission reductions of the European energy system. Recent policy updates have surpassed the initial GHG mitigation measures from 'solidEU,' making an update necessary. As the applied ESM 'ISAaR' was part of the original modeling landscape when developing 'solidEU', a coherent scenario update was possible for this study. In the updated version, the general developments within the energy system to reach the climate targets (e.g., expansion of RE generation units) follow those of the regulatory framework of the European Green Deal and the Ten-Year-Network-Development-Plan of the European Network of Transmission System Operators for Electricity [21]. The recently updated regulatory framework in Germany, the 'Easter Package' [11], is also considered. GHG ceilings for the optimization to reduce the direct (combustion-based) GHG emissions compared to 1990 levels are set according to the German government's targets (as of 2022), i.e., −65% by 2030, −77% by 2035, −88% by 2040 and − 100% by 2045, compared to 1990 [11,14].

Building upon 'solidEU,' the scenarios 'V2G' and 'Reference' used for this analysis include the novel possibility of modeling endogenous expansion of stationary BESS. Hereby, the options include both first- and second-life BESS. The ESM limits the availability of second-life batteries per modeled year to 50% of decommissioned BEVs' battery capacities, with a remaining capacity of 80% each. While the installation of stationary BESS is possible in both scenarios, the difference lies in the possibility of using BEVs as flexible BESS:

- In the **'Reference'** scenario, BEVs charge directly (uncontrolled) according to synthetic driving profiles by Fattler [24] based on infas [36].
- In the **'V2G'** scenario, the ESM includes the option of cost-optimized charging of BEVs. Besides unidirectional charging (V1G) that optimizes the time and duration of charging depending on the electricity prices, the ESM can apply bidirectional charging (V2G). This function enables the discharge of electricity back into the distribution grid, thus making BEV batteries available for the electricity system.

Kern and Kigle [43] describe the mathematical implementation of the charging strategies in 'ISAaR,' the underlying driving profiles, technical parameters, and respective data sources in detail. Section 3.2.2 summarizes relevant assumptions on BEVs for the LCI.

3.1.3. Functional unit

As a metric to investigate the systemic environmental effects associated with V2G charging, we determine and compare the hourly and annual average emission factors of power generation. The functional unit (FU) of impacts on the **system level** thus comprises the hourly national electricity generation in kilowatt-hours per year in Germany from the installed generation capacities for the time steps 2025–2045.

The FU for effects on the **technology level** encompasses the annual usage of a mid-sized passenger car and the mileage of an average German household over 10 years, starting from 2025. For determining the environmental break-even of BEVs with an ICEV, we assume a battery capacity of 70 kWh for BEVs. For the operation phase of BEVs, we use the 'V2G' scenario as the underlying scenario and thus apply the previously determined hourly emission factors of electricity generation. We determine the marginal changes, i.e., the operational emissions per charging strategy for an additional BEV not yet endogenously considered in the scenario results, causing further repercussions on the system in the case of V2G charging.

3.2. Inventory analysis and impact assessment

First, this section depicts the assumptions in the ESM concerning BEVs and charging strategies, as these are relevant for assessing both the effects on the system and technology levels. The steps for the inventory analysis and impact assessment for the effects of each level follow this.

3.2.1. Assumptions on BEVs in the scenarios

Table 2 outlines the assumptions regarding implementing BEVs in the scenarios modeled with the ESM. Next to the minimum state-of-charge (SoC) of 80% at departure, the SoC must not fall below 30% at any time. The average plug-in probability of 60% (i.e., times with BEV connection to the charging station) and a 79% probability of physical presence at the charging station result in the availability of 47% of the total battery capacity from BEVs as storage options in the ESM. The model considers electric vehicle supply equipment (EVSE) with a charging and discharging power of 11 kW as a commonly applied type for private charging. The annual mileage of an average driving profile slightly decreases over the years since 'ISAaR' considers changes in the modal split within the transport sector. While assumptions of Table 2 mainly stem from Kern and Kigle [43], the values on the user's preferences regarding the minimum SoC in our scenarios are adjusted to a more conservative value of 80% along with a higher average battery capacity of 70 kWh due to recent technical developments. Adjustments of these assumptions and the additionally considered plug-in probability of 60% result from discussions with BEV manufacturers.

3.2.2. Steps on the system level – German electricity generation

Fig. 2 illustrates the methodological steps of the inventory analysis and impact assessment for effects on the system level. Details on each step are outlined in the following.

Step 1: Creation of prospective LCI databases.

As a first step, we apply the *premise* framework (cf. [61]) to create pLCI databases for each modeled year to include future background system developments. As introduced in Section 1, *premise* transforms the LCI data from the Ecoinvent database by choosing a scenario from an IAM. We use the Ecoinvent version 3.8. For consistency with the underlying climate targets of our scenarios modeled with the ESM 'ISAaR,' we choose the climate policy scenario 'SSP2-PkBudg1100' from the IAM 'REMIND' (cf. [1]) for creating the pLCI databases. This scenario follows the socioeconomic pathway 'Middle of the Road' (SSP2) with medium challenges to mitigation and adaptation, see Riahi et al. [59] and restricts cumulative global emissions to a budget of 1100 Gt CO_2. As a result, *premise* creates separate pLCI databases for each five-year time step (2025–2045).

Table 2
Key assumptions for BEVs applied in the scenarios.

	Parameter	Values
Overall assumption (both scenarios)	Share of BEVs in new registrations	2025: 32% 2030: 65% 2035: 95% 2040: 95% 2045: 95%
	Total BEV stock, in Mio. units	2025: 4.6 2030: 12.9 2035: 22.6 2040: 30.3 2045: 34.7
	Average battery capacity, in kWh	70
	Average annual mileage, in km/year	2025: 14,048 2030: 14,052 2035: 13,936 2040: 13,763 2045: 13,612
	Charging/discharging power, in kW	11
	Charging/discharging efficiency	94%
Specific assumption for 'V2G 'scenario	Share of BEVs charging: unidirectional | V2G	50% | 50% of annual BEV stock
	Minimum safety SoC	30%
	Minimum SoC at departure	80%
	Plug-in probability of BEVs	60%
	Probability of physical presence at a charging station	79%

Step 2: Data processing on electricity generation per scenario.

The next step concerns data processing of modeling results from the ESM 'ISAaR' on the German electricity generation per scenario. The results from the ESM serve for two steps in the LCA: First, we derive a list of relevant technologies for the technology matching and the subsequent determination of the emission factor of electricity generation per technology EMF_{tech} (Steps 3 & 4). Secondly, 'ISAaR' provides hourly time series of electricity generation per technology $P_{el,tech,h}$ serving as an input for the impact assessment (Step 5).

Step 3: Technology matching.

As outlined in Vandepaer and Gibon (2018), one key challenge of combining the approaches of energy system modeling and LCA is matching the technologies, i.e., those of the scenario modeled with ESM and the LCI database. One common issue is different aggregation levels, which is also the case in our study since 'ISAaR' has a comparatively low resolution of technologies. For example, 'ISAaR' includes the technologies 'wind onshore' and 'wind offshore,' while the pLCI database further distinguishes between different sizes of wind turbines for both options. In this case, we apply a weighting to the composition of the 'ISAaR' technology with two or more technology types within the pLCA database (see Appendix A., Table A1). For relevant technologies, we consider changes over the years based on predicted market developments and simulation results on the annual expansion of installed capacities of the ESM. For the example of wind turbine sizes, we match the share of the existing power plant stock in 2025 with the pLCI dataset for the '1-3 MW turbine' and the share of additional installations per year with the '>3 MW turbine' according to market projections towards larger wind turbine sizes (cf. reviews by McKenna et al. [50], Pelser et al. [56]). Another challenge occurs for some technologies in our scenario that lack any equivalent in the pLCI database. This accounts for gas and oil power plants run by green methane, hydrogen, or synthetic diesel in the ESM 'ISAaR' future scenarios. In this case, we integrate a modified pLCI of conventional gas and oil plants, i.e., replacing conventional fossil fuels with green fuels. Assumptions for the adjustment stem from van der Giesen et al. [68] for synthetic diesel, as well as Volkart et al. [70] and Zhang et al. [78] for synthetic methane and hydrogen. Regarding the geographical scope, we apply the country-specific processes from the pLCI database for electricity generation in Germany ('GER') where available and Europe ('EUR') for the remaining processes. As a result of the matching process, there is one equivalent of a technology type in the pLCI databases per technology considered in the ESM 'ISAaR' (see Appendix A., Table A1).

Step 4: Impact assessment on electricity generation per technology.

Next, we determine an LCA-based emission factor per matched electricity generation technology EMF_{tech} using the open source LCA framework '*Brightway*' [52]. In line with the system boundaries, the GWP 100a is the impact category, and the 'IPCC 2013 no LT' the impact assessment method. As a result of Step 4, each electricity generation technology of the ESM has one emission factor per five-year time step in the unit of CO_2-equivalents per kilowatt-hour of electricity generation.

For the emission factors of solar power, results between 70 and 80 gCO_2e/kWh by 2020 are comparatively high to those in the literature (e.g., Bartie et al. [8], reviews by Asdrubali et al. [7] and Weyand et al. [72]). With a geographical focus on Germany, we build upon the factors determined by Hengstler et al. [32] of 50 gCO_2e/kWh (slanted roof) and 48 gCO_2e/kWh (open ground). The study considers recent market developments on the composition of module types (see Appendix A., Table A1), production location, module efficiency, performance ratio, lifetime, as well as location-based parameters for installations in Germany (e.g., solar radiation of 1,200 kWh/(m^{2}*a)). To generate prospective values for the investigated five-year steps 2025–2045, we use the values from Hengstler et al. [32] for the base year 2020 and apply an equal percentage of decrease (delta) between the time steps as those resulting from the LCA when using the pLCI databases.

Step 5: Impact assessment on electricity generation per scenario.

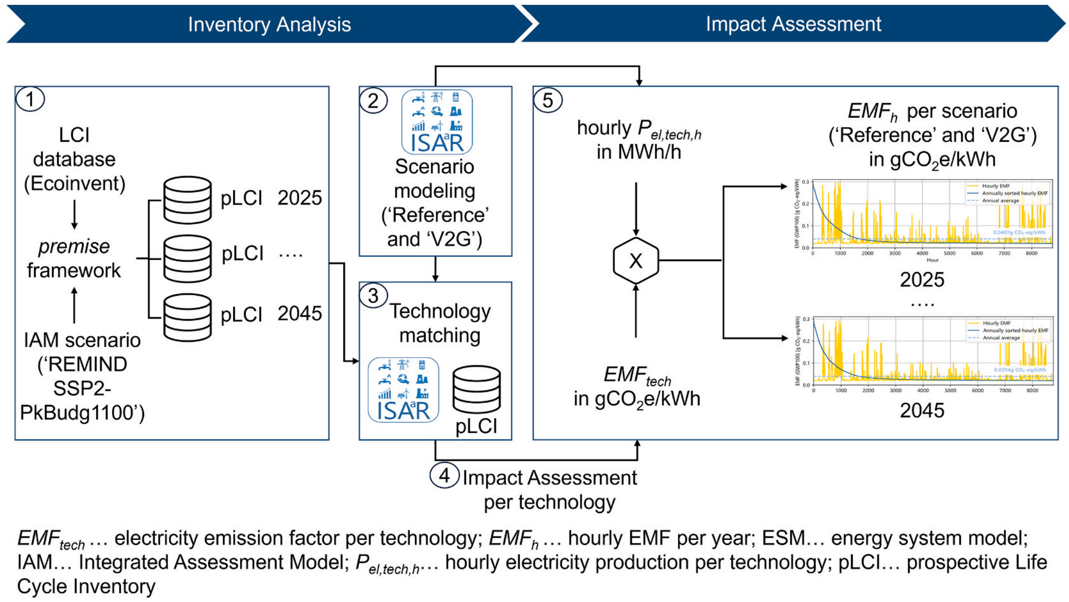

Fig. 2. Methodological approach to determine hourly emission factors (EMF) of electricity, following a pLCA-based ex-post assessment of ESM results.

Finally, we determine the hourly emission factors of electricity generation EMF_h per scenario. For each hour h of the year, we multiply the respective shares of electricity generation per technology $P_{el,tech,h}$ (results of Step 2) with the LCA-based emission factor per generation technology EMF_{tech} (results of Step 4) for all technologies.

$$EMF_h = \sum_{tech} EMF_{tech} * P_{el,tech,h}$$

As a result, we receive hourly time series on the emission factors of national electricity generation for the 'V2G' and the 'Reference' scenarios, respectively. Total emissions EMF_{tot} are calculated as

$$EMF_{tot} = \sum_{h} EMF_h.$$

3.2.3. Steps on the technology level – Impact of battery electric vehicles

To evaluate the effects of V2G charging on the technology level, we first analyze the changing operational emissions of BEVs depending on the charging strategy. To interpret the results, we determine the environmental break-even with gasoline-powered ICEVs (see Section 3.3). The LCI thus includes data on both vehicle types' production and operation phases. The following steps for the inventory analysis and impact assessment on the technology level are outlined.

Step 1: Data collection for production and operational emissions of vehicles.

For determining the operational emissions of BEVs per charging strategy, we use two data sources: First, the hourly emission factors of German electricity generation of the 'V2G' scenario as determined for the system level perspective (Section 3.2.2). Since these factors are built upon the hourly shares of electricity generation, we consider the different electricity mixes when determining the operational emissions of BEVs for charging and discharging. Secondly, the hourly charging profiles of an average driving profile per BEV serve as an input, resulting from the ESM per five-year time step. To determine the respective environmental break-even with ICEVs, we investigate an operation starting in 2025. As the starting point of the emission balance for each vehicle type in 2025, it requires the determination of the footprint from the production phase. Since this study focuses on the impact depending on the charging strategy rather than the production phase, we use secondary data on production emissions outlined in Buberger et al. [13]. In line with our scope, the values represent the impact category of 'climate change' for a mid-sized BEV and ICEV passenger car, respectively. Buberger et al. [13] distinguish between emissions for the vehicle body per weight and, in the case of BEVs, for the battery pack per capacity. Following Buberger et al. [13] and Xu et al. [76], we assume a lithium-ion battery as a widely applied battery type for BEVs. Table 3 summarizes applied data on production emissions, vehicle specifications, and respective sources. The battery capacity stems from the assumptions within our scenarios (see Section 3.1.2), technical data sheets on comparable mid-sized passenger cars (Hyundai IONIQ 5; VW Passat for the ICEV) provide vehicle weights [2,3]. These data sheets further provide the average fuel consumption to determine operational emissions for ICEVs.

Step 2: Impact assessment of vehicles' operational emissions.

For operational emissions of the ICEV, we multiply the annual mileage from the ESM with the average fuel consumption (Table 3) and the emission factor of gasoline derived from the pLCI databases. For the investigated 10-year time frame of operation starting from 2025, we apply the pLCI values for the process 'market for gasoline, unleaded' of 2025, 2030, and 2035, with a linear interpolation for the years between these time steps.

For BEVs, the operational emissions per year and charging strategy result from the intersection of the hourly emissions of electricity and the charging profiles. For uncontrolled and V1G charging, thus, the charged electricity volumes per hour are multiplied with the respective hourly

Table 3
Data for assessing effects on the technology level and break-even between BEVs and ICEVs.

	Parameter	Values	Source
Production emissions	Production emissions per vehicle body, in $kgCO_2e/kg$	4.56	Buberger et al. [13]
	Production emissions per battery pack, in $kgCO_2e/kWh$	83.6	Buberger et al. [13]
BEV specifications	Vehicle body (unladen weight excl. Battery weight), in kg	1,532	ADAC [2]
	Average battery capacity, in kWh	70	ESM 'ISAaR'
	Average consumption, in kWh/ 100 km	17.3	ESM 'ISAaR'
ICEV specifications	Vehicle body (unladen weight) in kg	1,474	ADAC [3]
	Average consumption (gasoline), in liters/ 100 km	6.4	ADAC [3]

emission factor as previously determined for the 'V2G' scenario. In the case of V2G charging, the BEV fulfills two functions, i.e., charging for operating the BEV (driving) and charging/discharging for the secondary purpose as a storage option in the energy system. For dealing with the allocation of operational emissions, two perspectives exist:

- *'Physical allocation'*: In this case, only the emissions from driving the BEV are considered. Out of the total charging processes per year, the emissions from the charged electricity that is subsequently discharged (incl. losses) are excluded from the balance (equal method for determining emissions of uncontrolled or unidirectional charging).
- *'System expansion'*: As a second perspective, an allocation is avoided by expanding the system boundaries from the BEV to its connection with the electricity grid and thus include its secondary purpose. Accordingly, we consider the emissions of all charging hours with a positive sign. For discharged electricity volumes in the case of V2G charging, we assume a substitution of electricity generation in the respective hours. Therefore, discharged electricity volumes are associated with a negative sign and multiplied by the respective emission factors of that hour (grid mix). Discharging is thus 'credited' to the BEV by reducing operational emissions.

Previous investigations focusing on the impact of V2G charging on the technology level, such as by Fattler [24], apply the approach of 'system expansion.' In our study, we investigate the impact on the system level in the first part of the analysis and thus include the systemic benefit in the hourly emission factors. Therefore, the 'physical allocation' is more feasible to conclude on the impact on the technology level. Following the ISO norms 14,040:2021/14044:2006, we outline the results for both approaches to deal with the allocation and reflect on the differences in Section 4.3.

3.3. Interpretation

For evaluating and discussing results on the **system level**, we outline the resulting total GHG emissions of electricity generation, the load-weighted average emission factors, and the standard deviation (σ) to compare the scenarios and years. The standard deviation illustrates the fluctuation of the emission factors within one year, i.e., the spreads between the factors. Besides these metrics, we illustrate the time series of emission factors per hour of 2035 for both scenarios, including sorted values (i.e., annual duration curves). For validation and evaluation of emission peaks in certain hours, we compare these to the hourly electricity generation mix in the respective time steps as an output from the ESM.

Regarding the **technology level**, we first evaluate the annual operational emissions per BEV and year depending on the charging strategy, i.e., uncontrolled, cost-optimized unidirectional (V1G), and bidirectional (V2G). For V2G charging, both allocation methods are applied (see Section 3.2.3). Determining the environmental break-even per charging strategy serves for comparison with ICEVs.

4. Results

First, this section includes the modeling results from the ESM 'ISAaR' (Section 4.1), serving as an input for the inventory analysis and impact assessment. Next, we outline the results of the LCA-based evaluation on the environmental effects of V2G charging on the system (Section 4.2) and technology level (Section 4.3).

4.1. Electricity generation and storage resulting from the energy system model

Overall, results on the scenarios modeled with 'ISAaR' show the necessity of a massive expansion of RE and storage capacities to reach the climate targets. Fig. 3 outlines the net electricity generation (excluding self-consumption of power plants) and the share of RE therein. Due to equal underlying climate targets, including the phase-out of coal-fired power plants by 2030, similar developments occur in the two scenarios. Up to 2030, the ESM limits the expansion of RE capacities as anchored in the national targets (exogenously defined within the optimization). Fig. 3 shows an exceptionally high increase in RE power generation from 2035 onwards, as the ESM no longer sets a fixed limit (endogenous expansion). In the following years, there was an increased demand for electricity besides electromobility, e.g., caused by electrification of the building sector (space heating) or hydrogen production used for industrial processes. From 2025 until 2045, both scenarios thus show a significant increase in the German electricity generation from approx. 600 TWh up to 1240 TWh to meet the electricity demand. For comparison, German electricity generation in 2022 amounted to 571 TWh [18]. Considering national climate targets as boundary conditions in the model (e.g., GHG reduction, coal, and nuclear phase-out), the share of RE in total electricity generation starts at two-thirds in 2025 (compared to 44% in 2022 [18]) and reaches 100% by 2045. Next to wind power, contributing with the majority of 62% in total generation in 2045, the high share of solar power (31%) leads to a future electricity generation highly dominated by volatile RE. Gas-fired power plants use hydrogen ('H_2-Ready') or synthetic fuels and operate on very low full load hours for system stability during RE shortage.

Fig. 4 zooms into the differences in electricity generation between the two scenarios. 'V2G' results in higher shares of RE except in the year 2025, where electricity production from coal increases by 0.4 TWh, leading to slightly higher total emissions (see Table 4) as GHG emission targets are not yet in place. With the phase-out of coal-fired power plants by 2030, as decided by the German government, this effect disappears. The comparatively most remarkable difference between the scenarios occurs in the year 2035. In 'V2G', there is an increase in generation from solar power (positive values) and a decrease in wind power (negative values) compared to the 'Reference' scenario. This is due to the above-mentioned additional degree of freedom in optimizing the ESM when changing from exogenous to endogenous capacity expansion of RE from 2030 to 2035.

Furthermore, the scenarios entail a change in necessary electrical storage capacity. While hydrogen storage capacities serve for seasonal balancing and reach 39 TWh by 2045 in both scenarios, Fig. 5 shows significant differences in BESS capacities. Being a cost-optimized ESM, the 'V2G' scenario shows a clear preference for utilizing BEV batteries compared to stationary BESS due to the lower underlying cost parameter per capacity. The available potential of BEV batteries is thoroughly used in each modeled year. Showing a cost advantage over conventional (first-life) BESS, second-life BESS cover the remaining small share of required storage capacity in the 'V2G' scenario. In contrast, the restricted availability of second-life BESS in the medium-term (cf. Section 3.1.2) requires the expansion of 117 GWh of first-life BESS capacity in the 'Reference' scenario by 2030. Parametrized in the ESM with a lifetime of 15 years, the first-life BESS leave the system of the 'Reference' scenario by 2045 and are substituted by available second-life BESS. The installed electrical storage capacity of 287 GWh in the 'Reference' scenario will be less than one-quarter of 1,229 GWh in the 'V2G' scenario (grey bars in Fig. 5). While the capacities of stationary BESS offer availability without restrictions, those of BEV batteries are limited to 47% of capacity due to technical specifications and the driving behavior (see Table 2), e.g., 582 GWh out of 1,229 GWh in 'V2G' in 2045 (red dots in Fig. 5). Despite these limitations, the total available storage capacities in the cost-minimized system in the 'V2G' scenario vastly exceed those in the 'Reference' across all years. The improved integration of solar power in 'V2G' (see Fig. 4) thus results from this overall increased storage capacity, providing a higher potential to shift the midday generation peaks to the evening and night hours.

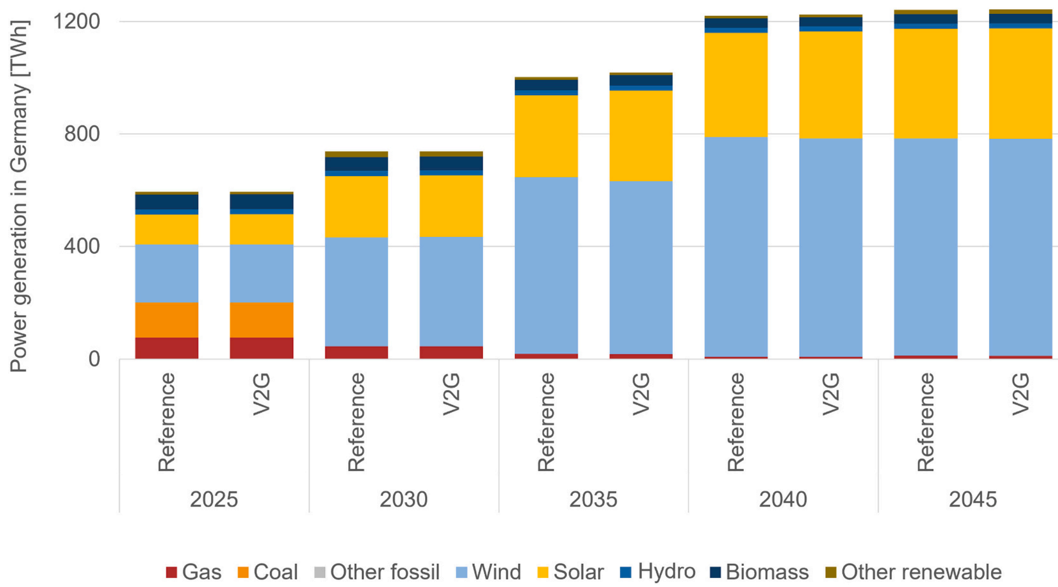

Fig. 3. Modeling results of 'ISAaR' on the German electricity generation per scenario from 2025 to 2045.

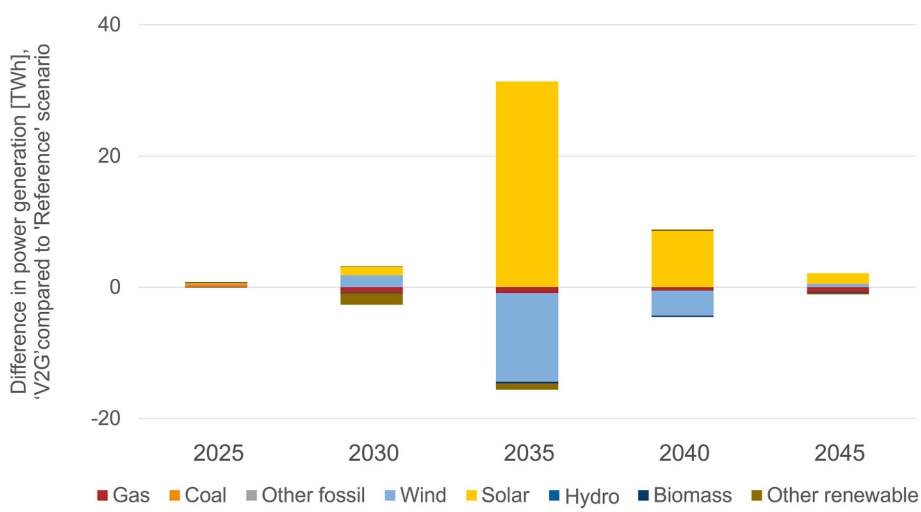

Fig. 4. Modeling results of 'ISAaR' on the difference between German electricity generation in the 'V2G' compared to the 'Reference' scenario from 2025 to 2045.

Table 4
Resulting emissions and emission factors of electricity generation in Germany per scenario.

Scenario	Reference	V2G	Reference	V2G	Reference	V2G
	Total GHG emissions in mio. tCO_2e		Average emission factor, load-weighted, in gCO_2e/kWh		Standard deviation σ of hourly emission factors, in gCO_2e/kWh	
2025	195.4	196.0	329	330	143	141
2030	48.0	47.1	65	64	73	72
2035	31.6	31.2	32	31	45	43
2040	29.3	29.3	24	24	28	28
2045	26.6	26.6	21	21	12	12

4.2. Impacts on emissions of electricity generation

Table 4 outlines the resulting total GHG emissions of German electricity generation (EMF_{tot}), annual averages of the load-weighted emission factor, and the standard deviation σ of hourly emission factors of electricity generation per scenario and year. All values are LCA-based (GWP 100a) (see Section 3.1). Results show a significant decrease in GHG emissions over the investigated time frame in both scenarios due to equal underlying climate targets. The most significant decrease occurs from 2025 to 2030, caused by the exogenously determined RES expansion to reach the ambitious climate targets the German government set for 2030 (i.e., GHG reduction by 65% compared to 1990). Comparing the scenarios, total GHG emissions in 'V2G' decrease compared to the 'Reference' scenario throughout the years except for 2025. The increase by 0.6 mio. tCO_2e can be explained by the additional electricity from coal-fired power plants, as outlined in Section 4.1. This only marginally impacts the average load-weighted emission factor of 300 gCO_2e/kWh in 'V2G' compared to 329 gCO_2e/kWh in the 'Reference' scenario. In the medium-term, V2G charging offers slight reductions of systemic emissions, i.e., in the time frame 2030–2035 (see Table 4). From 2040 onwards, V2G charging does not affect any indicator of systemic GHG emissions compared to a scenario with stationary BESS.

Furthermore, slight differences between the scenarios exist when assessing hourly emission factors and their standard deviations. As the year with the comparatively most significant differences in the standard deviation, Fig. 6 illustrates the resulting hourly time series and the

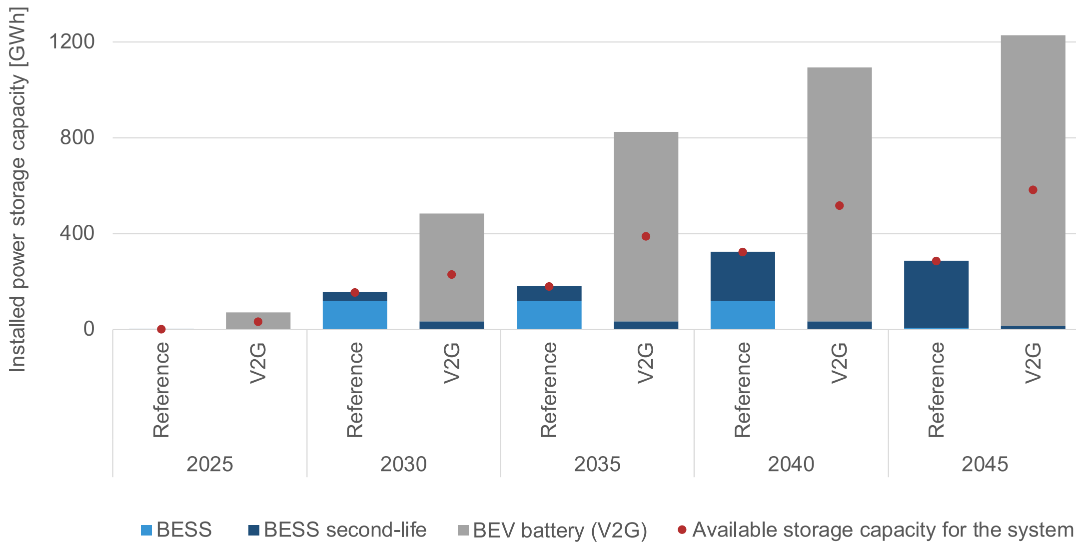

Fig. 5. Modeling results of 'ISAaR' on the German electricity storage capacity per scenario from 2025 to 2045

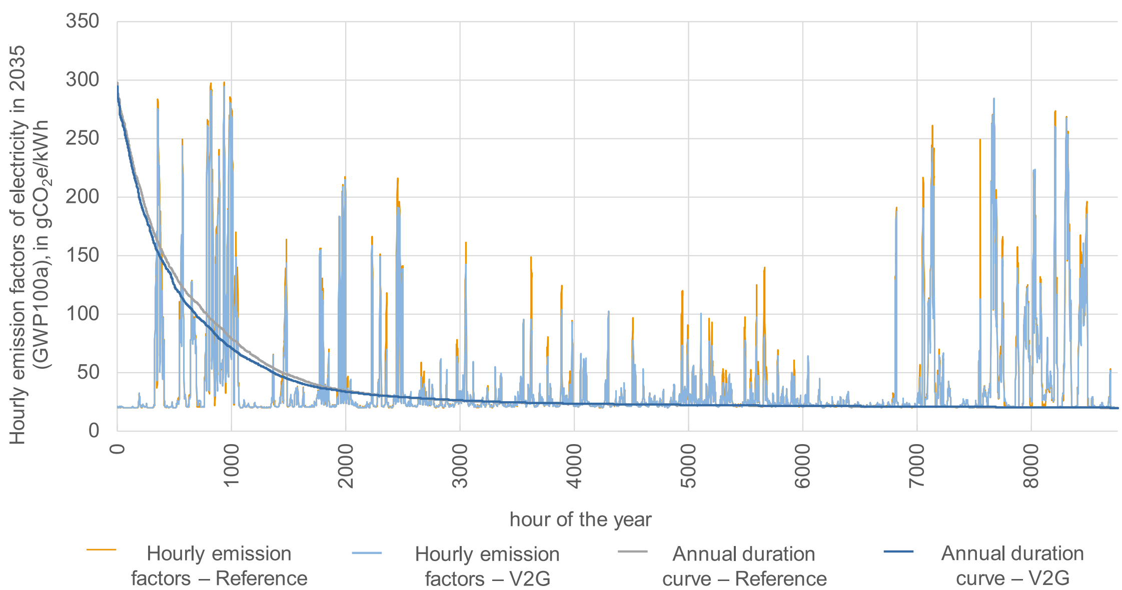

Fig. 6. Hourly emission factors of electricity generation, including the sorted values as the annual duration curve per scenario, the year 2035.

sorted annual duration curves per scenario for 2035. The graph shows overall lower levels of emission peaks in the 'V2G' (light blue) compared to the 'Reference' scenario (orange). This can be explained by the larger storage capacity in the 'V2G' compared to stationary BESS in the 'Reference' scenario (see Section 4.1) and the resulting greater potential for peak shaving in hours of high generation from RES (e.g., PV in summer months). The sorted values of the annual duration curve further prove this development, i.e., showing fewer hours and lower levels of high emission factors in the 'V2G' (dark blue) compared to the 'Reference' scenario (grey). By 2035, the maximum emission peaks will reach 298 and 294 gCO2e/kWh in the 'Reference' and 'V2G' scenarios.

When modeling results for the highly decarbonized German electricity sector in 2045 are investigated, emission factors decrease to a maximum of 111 and 96 gCO2e/kWh in the 'Reference' and 'V2G' scenarios, respectively. The reduction can be attributed to the higher storage capacity dispatchable at hours with high residual loads, substituting electricity from green gases (i.e., synthetic methane, hydrogen). Emission peaks result from hours with a high share of electricity generation from green gases due to overall low efficiency and the emission-intense upstream chain of biogas-fired power plants. Supplementary data in Appendix B. provides hourly time series of emission factors per scenario and year.

To conclude, V2G charging expands total available storage capacities and leads to an increased integration of fluctuating generation from RE in a cost-minimized system with endogenous expansion of RE. From a system level perspective, V2G charging offers a relevant flexibility option, serving as a bridge to accelerate the transition towards a decarbonized energy system based on volatile RE. Thus, the electricity system's GHG emissions decrease faster in the medium-term than without V2G. Yet the overall contribution to mitigating emissions at the system level is insignificant and continues to diminish with the ongoing decarbonization of electricity generation in the long-term. In the 'Reference' scenario, thus, an equal reduction of GHG emissions is reached through stationary BESS instead of BEV batteries. Long-term environmental benefits through V2G charging, however, could occur regarding raw materials as the scenario shows a decreased demand for stationary BESS. Being out of scope in this study, the potential environmental benefits of changing electrical storage capacities are discussed in Section 5.

4.3. Impacts on emissions of battery electric vehicles

Regarding the changing impact on the technology level, we first determine GHG emissions of BEVs per charging strategy when operating in the 'V2G' scenario system. We apply resulting hourly emission factors from the system level perspective along with the charging profiles used in the 'V2G' scenario (see Section 3.1). Fig. 7 illustrates the annual results for the modeled time frame of uncontrolled, uni- (V1G), or bidirectional (V2G) charging for a mid-sized BEV with an average mileage as outlined in Table 2.

For V2G charging, the results include both cases of dealing with the allocation (see Section 3.2.3). When excluding the electricity charged and discharged for the secondary purpose of electricity storage, i.e., 'physical allocation,' the annual operational emissions of BEVs correspond to those of V1G. This is because a cost-optimized charging strategy is pursued in the V1G and V2G cases, e.g., charging during hours with low electricity prices. In the case of 'system expansion,' avoided emissions on the system level are included for evaluating the impact of BEVs. This occurs when feed-in during comparatively low RE generation periods reduces emissions in the electricity system by replacing generation from more GHG-intense power plants. If resulting reductions from discharging exceed the impacts caused by charging, operational emissions in Fig. 7 reach a negative sign.

By 2025, annual operational emissions of 632 gCO_2e/BEV (45 gCO_2e/km) for uncontrolled charging significantly decrease through V1G and V2G charging, reaching 326 gCO_2e/BEV (26 gCO_2e/km) and 173 gCO_2e/BEV (12 gCO_2e/km). Fig. 7 shows a further reduction of absolute operational emissions across all three charging strategies from 2025 to 2030. This is due to the strong increase of RE in the total electricity generation from 2030 onwards (see Section 4.1). Similar to results on the system level, the highest potential occurs in the medium-term: By 2030, emissions will decrease by 50% from 144 $kgCO_2e$/BEV (10 gCO_2e/km) for uncontrolled charging to 72 $kgCO_2e$/BEV (5 gCO_2e/km) in cases of V1G / V2G excluding systemic reductions ('physical allocation'). When including systemic reductions of V2G charging ('system expansion'), annual operational emissions decrease by approx. 200% and reach −141 $kgCO_2e$/BEV (−10 gCO_2e/km). Unlike 2025, the following years offer more charging hours with emissions close to zero (from RE), while discharging leads to a substitution of electricity generation in hours with comparatively higher GHG intensities. In later years, the overall decarbonization of electricity production and thus the lower standard deviation σ (see Table 4) decreases the potential to shift the charging hours to less GHG-intense hours. In the long-term, i.e., by 2045, the operational emissions reach 3 gCO_2e/km (uncontrolled), 2 gCO_2e/km (V1G/ V2G physical allocation), and − 0.1 gCO_2e/km (V2G system expansion).

Fig. 8 outlines the environmental break-even with a conventional ICEV (gasoline) as the second result of the research question concerning the technology level. The starting point on the y-axis shows the LCA-based impact from the investigated mid-sized vehicles' production, being almost double for BEVs with 12.8 tCO_2e compared to 6.7 tCO_2e for ICEVs. The x-axis reflects the additional emissions from the operation phase over the 10-year time frame, including both perspectives for dealing with the two functions of V2G charging. Overall, the evaluation in Fig. 8 shows the potential of BEVs to decrease GHG emissions compared to ICEVs across all charging strategies in the long-term. The 'environmental amortization time' of BEVs in the case of uncontrolled charging amounts to 3 years. In the cases of V1G / V2G with physical allocation, a reduction by approx. 10% to 2.7 years occurs. When crediting systemic reductions of V2G charging to the BEV, the break-even decreases significantly by almost one-fifth (18%) to 2.5 years compared to uncontrolled charging. Considering the annual mileage (see Table 2) and a linear change between the five-year steps, this amounts to a break-even at approx. 42,184 km (uncontrolled), 38,411 km (V1G/V2G physical allocation), and 34,979 km (V2G system expansion).

The total emissions of an investigated mid-sized ICEV over 10 years (2025–2035) amount to 32.4 tCO_2e, compared to 15.6 tCO_2e for a BEV applying uncontrolled charging. Thereof, 2.8 tCO_2e result from the operation. These operational emissions further decrease to 1.6 tCO_2e in the cases of V1G / V2G with physical allocation and even reach a net decrease of −0.3 tCO_2e when crediting systemic reductions to the BEV in the V2G case. Compared to the initial production-based footprint of 12.8 tCO_2e for the BEV, the reduction potential during the operation phase is relatively marginal, further discussed in Section 5.

5. Discussion

In the following, we reflect on our core findings on the environmental effects associated with a diffusion of V2G charging, answered through the two analysis parts on impacts within the electricity system and the technology level. We contextualize our results in scientific literature and point out the limitations of this study.

1. How does a diffusion of V2G charging and, thus, the availability of BEVs as flexible storage options impact the electricity system and associated life-cycle GHG emissions of electricity generation?

To investigate the effects of V2G charging on the **system level**, we developed a framework to determine changes in prospective life-cycle

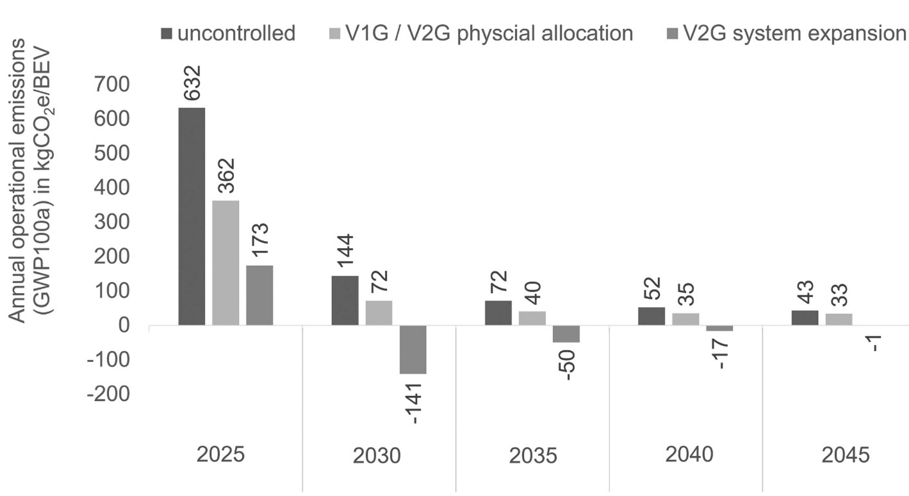

Fig. 7. Annual operational emissions per BEV from 2025 to 2045, depending on the charging strategy.

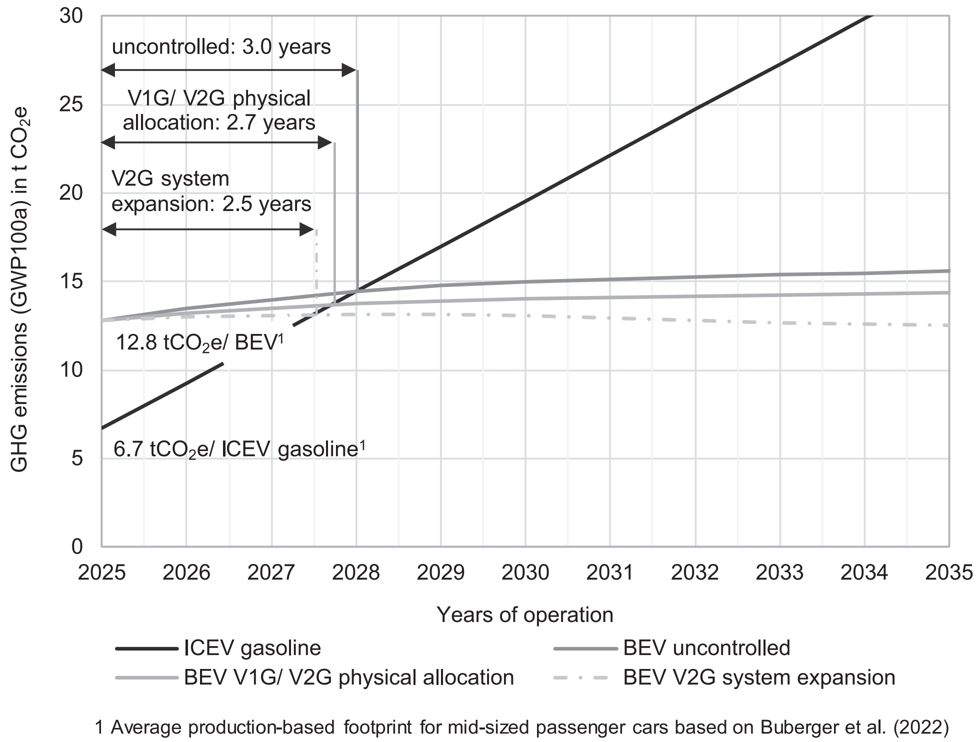

Fig. 8. Environmental break-even of BEVs compared to ICEV (gasoline) depending on the charging strategy, modeled for a BEV operating in the 'V2G' scenario.

emissions of electricity generation. The method encompasses a comparative ex-post assessment of scenarios on the electricity system, modeled with a cost-optimized ESM. We conduct a consequential approach by investigating scenario results that consider repercussions within the system depending on the diffusion of V2G, e.g., affecting total storage availability or generation from RE. Since V2G charging is a novel technology at an early stage of market diffusion, we model future scenarios and adjust the fore- and background system through a pLCA to include future developments. We prove the method's suitability by applying it to two scenarios for Germany's future electricity system. Once there is historical data available on where V2G has impacted local and systemwide emissions, a sensitivity analysis for the accuracy of the modeled results is possible. This can be done by reviewing the modeling results compared to historical performances.

Looking at the determined GHG emissions for the investigated future scenarios, the 'V2G' and the 'Reference' climate policy scenarios result in an annual average emission factor of approx. 300 gCO_2e/kWh by 2025. Our results seem reasonable compared to German electricity's emission factor of 498 gCO_2e/kWh in 2022 (Icha and Kuhs 2023). Similarly, applying BEV batteries as storage options does not affect the long-term life-cycle GHG emissions of national electricity generation compared to a scenario with stationary BESS. Thus, both scenarios lead to equal annual emission factors of 21 gCO_2e/kWh electricity generation in a cost-minimized system by 2045. For comparison, Seckinger and Radgen [63] project a 29 gCO_2e/kWh emission factor for German electricity in a climate policy scenario for 2050. In contrast to our approach, the study assumes the initial government's GHG reduction goal (−95% by 2050 vs. updated goal of −100% by 2045 compared to 1990 levels) and excludes a pLCA approach. The slightly higher emission factor in Seckinger and Radgen [63] thus fits the magnitude of our results. In the years between (2030–2035), however, V2G charging contributes to an accelerated integration of volatile RE and, thus, a faster decrease of both total GHG emissions of electricity generation and emission peaks. It is, therefore, of particular importance to accelerate the development and market integration of V2G to fully utilize its potential to bridge the transition.

While effects on GHG emissions with a focus on electricity generation are not significant, especially in the long-term, comparing the life-cycle-based impacts associated with electrical storage options could add another angle to the assessment. According to a review by Gutsch and Leker [31], studies published from 2019 onwards conclude on a GWP between approx. 40–170 $kgCO_2e/kWh$ per BESS capacity for different chemistries. The required 117 GWh of first-life BESS capacity entering the 'Reference' system by 2030 would cause a GWP of 4.7–19.9 mio. tCO_2e (excluding prospective investigations). In contrast, the electrical storage demand in the 'V2G' scenario is almost entirely covered by BEV batteries and a remaining small share of second-life BESS. Although a lower GWP is expected in the future, e.g., through decarbonization of electricity used in the production phase, a substitution of stationary BESS could further decrease impacts on the system level. Reduced material demands not only affect climate change but also yield savings in other impact categories, as demonstrated in studies on repurposed lithium-ion batteries by Schulz-Mönninghoff et al. [62] and Koroma et al. [46] for resource depletion and mineral resource scarcity, respectively.

2. How do systemic consequences on electricity generation impact the operational life-cycle GHG emissions of BEVs and the environmental break-even with ICEVs, depending on the charging strategy?

By applying GHG emissions of electricity generation from a scenario considering the diffusion of V2G charging, we include repercussions within the system when evaluating the **technology level**. Our results on the impact of BEVs depending on the charging strategy provide insights for researchers, the automotive industry, or policymakers. Besides giving results for an operation in Germany, we methodologically guide further assessments of V2G charging at the technology level by outlining and discussing two approaches for allocating operational emissions.

The determined break-even of BEVs with ICEVs ranges between 42,184 km and 34,979 km. These mileages are comparatively lower than specified in other German-focused LCA studies (see review by Wohlschlager et al. [74]), on average showing a break-even after approx. 50.000 km for a small passenger car. The lower values in our study primarily result from the pLCA approach, assuming a starting point by 2025 and lower GHG intensities of the electricity mix compared to the status quo.

Compared to the literature, Arvesen et al. [6] use a pLCA approach to investigate the emissions of innovative charging strategies (unidirectional) for two climate policy scenarios on a European level. The authors conclude on an impact of charging between 19 gCO_2e/km and 12 gCO_2e/km by 2050, which is comparatively higher than our results of 2 gCO_2e/km (V1G) for 2045. As the study is conducted for Europe rather than Germany and thus follows less ambitious climate targets, however, the underlying average electricity generation mix of approx. 100 gCO2e/kWh by 2050 is used. Furthermore, the investigated use case represents day charging and night charging, i.e., shifting charging hours into specific time frames of the day. Our study contributes to this by including the optimization of V2G charging in the ESM, and thus, the hours of (dis-)charging follow a price signal.

Overall, these insights contribute to the overarching question about the consequences of V2G charging on prospective life-cycle GHG emissions. The ongoing integration of BEVs and emerging charging strategies in the energy system increase the interaction between the technology and system levels. Concluding on the associated medium and long-term life-cycle impacts thus requires a combined approach: determining systemic repercussions and considering these when assessing BEVs operating in such a future system. This article outlines a methodologically consistent set-up to investigate both effects, including equal underlying scenario assumptions and pLCI databases. The comparative assessment of cost-minimized climate policy scenarios shows that V2G charging offers an economical storage option and accelerates the integration of RE in the medium-term. From an energy system perspective, this demonstrates the relevance of implementing novel charging strategies, especially bidirectional charging, in upcoming years. When considering the systemic benefits of V2G charging on the technology level, BEVs' operational emissions can be decreased by up to −200%. Again, these positive effects primarily emerge in the medium-term and rely on a high customer participation in V2G operation. Reporting environmental benefits could enhance user acceptance, a condition for a large-scale implementation. Case studies on V2G charging in Europe and the U.S. [29,66] further conclude on promising customer revenue potentials. Besides technological advancements (e.g., battery capacity, EVSE interoperability, and charging power), realizing these potentials requires the right regulatory conditions and market rules. Along with implementing suitable techno-economic conditions, industry and political decision-makers can contribute to realizing a long-term decrease in environmental impacts. This can be achieved by substituting stationary BESS by BEV batteries and shifting the focus to reducing impacts resulting from production and associated upstream chains.

Limitations

Despite the geographical scope of the German electricity system in our analysis, scenarios are modeled with a cost-optimized European ESM. The resulting national changes indirectly include repercussions within the European system as the model considers Germany as part of the European electricity market. While these effects are included in the resulting values for Germany, the analysis excludes an investigation of the hourly emission factors of other countries. Following the outlined methodological steps (see Section 3.2.2), a transfer of our framework to different geographical scopes is possible. Such a transfer requires an ESM for any geographical scope that provides hourly time series of electricity generation per technology, serving as an input for the impact assessment and conducting a technology matching. It further requires the choice of an adequate region provided in the pLCA database and a scenario for creating the pLCI databases consistent with the underlying climate targets of the ESM.

Considering the scenario choice, we are aware that both the 'V2G' and 'Reference' cases tend to be extreme scenarios. Despite the restrictions due to the user behavior (see Table 2), the 'V2G' scenario assumes a high availability of BEVs as flexible storage options that apply a cost-optimized strategy. In the future, new business models such as V2H or V2B (see Section 1) might enter the system. While our selected scenarios are specifically tailored to investigate the effect of cost-optimized V2G charging in the current study, the methodology of this article and emission factors provided in the supplementary material can serve to evaluate other charging strategies.

To investigate the systemic repercussions of using batteries from BEVs within the electricity system, the scope of the comparative analysis focuses on all-electric vehicles. Other powertrain technologies, such as fuel cell electric vehicles, were excluded from this assessment. Plug-in hybrid vehicles were excluded due to the comparatively low battery capacity and, thus, the limited flexibility potential of V2G.The system boundaries for evaluating the impacts on the technology level include the production and operation life-cycle phases of BEVs and ICEVs. While we consider future developments over the 10-year time frame of operational emissions resulting from the conducted pLCA, we do not modify the production-based footprints. When assessing the break-even with a starting point further in the future, it would require an adjustment of the production-based impact. With this regard, Xu et al. [76] highlight that the projected improvement of the battery density of BEV batteries has the potential to decrease GHG emissions of BEVs in the future. Since we assume 2025 as the start year, applying the recent LCA values from Buberger et al. [13] is feasible for this study. Furthermore, battery aging is another influencing factor of both the life-cycle-based impact of BEVs and systemic effects. Xu et al. [76] include a battery degradation linearly depending on the charging volumes but conclude that diverse additional factors such as temperatures or the SoC should be considered in the future.

6. Conclusion & outlook

This article analyzes the impact on life-cycle GHG emissions caused by a diffusion of V2G charging. The novelty lies in our combined approach: First, we determine the medium and long-term effects caused by repercussions on electricity generation (system level). Secondly, resulting hourly GHG emissions allow us to incorporate systemic repercussions when evaluating BEVs operating in such a future system (technology level). Combining energy system modeling and a pLCA approach, our framework systematically considers future developments in the technological system landscape and the technologies' LCI. Applied to the German electricity sector from 2025 to 2045, we prove the method's suitability and outline the relevance of V2G charging to decrease impacts from both perspectives.

On the **system level**, BEV batteries function as a cost-effective storage option and increase the overall electrical storage capacity compared to a cost-minimized system with stationary BESS. This results in an accelerated integration of RE while lowering emission peaks by substituting generation from more GHG-intense generation in times of discharging. While both climate policy scenarios result into equal climate impacts of electricity generation by 2045, V2G charging accelerates this transition in the medium-term (2030–2035). Besides the insignificant long-term effects on GHG emissions, the application of V2G potentially decreases impacts related to resource depletion and mineral resource scarcity by decreasing the demand for stationary BESS.

Incorporating these effects when assessing the **technology level**, V2G charging significantly decreases the impact of BEVs during the transition towards climate neutrality. By 2030, smart charging will reduce operational emissions by 50% compared to uncontrolled charging. When considering the benefits of the secondary purpose of BEVs in the case of V2G charging, operational emissions decrease by almost 200%. Although the technology is a relevant flexibility for the energy system and contributes to bridging the transition, the positive effects on GHG emissions decrease with the ongoing decarbonization of electricity generation. Manufacturers should thus focus on reducing impacts from other life-cycle phases, e.g., by improving production processes. Furthermore, a diffusion of V2G requires large-scale customer participation. Economic incentives, technological advancements and the right regulatory conditions constitute a major lever for this.

For further research, we suggest expanding the environmental assessment of V2G charging. First, including battery aging and advancements of the battery modules could contribute to more detailed modeling in the ESM and potentially affect the break-even with ICEVs. Secondly, the underlying governmental climate targets and the total amount of BEVs remain equal in our investigated scenarios. This choice of scenario design is appropriate for the goal of investigating the impact of the charging strategy. Investigating other charging use cases (e.g., V2B, V2H) or its application for different modes of transport (e.g., public transportation, car sharing) could contribute to further deriving policy suggestions for a mobility transition beyond focusing on the electrification of individual passenger transport. Lastly, we suggest expanding the system boundaries to assess systemic repercussions on installed storage capacities while including impact categories associated with raw materials, i.e., resource or metal depletion.

Overall, this work conducts a future-oriented impact assessment of the effects caused by a large-scale diffusion of V2G charging strategies in the medium and long-term. We outline, evaluate, and discuss systemic repercussions as relevant inputs to assess technologies operating in such a future system. The article thus provides methodological guidance for LCA professionals to assess emerging use cases by linking the system and technology levels while considering future developments. Applied to climate policy scenarios of Germany, the results offer insights into the role of V2G charging in the energy transition. Industry and political decision-makers can consider and react to the identified potential effects in the medium and long-term before a market diffusion.

CRediT authorship contribution statement

Daniela Wohlschlager: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stephan Kigle:** Writing – original draft, Methodology, Investigation, Formal analysis. **Vanessa Schindler:** Writing – original draft, Investigation. **Anika Neitz-Regett:** Writing – review & editing, Supervision. **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

Hourly time series of determined emission factors of electricity per scenario and year can be found in the supplementary material of this article.

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Appendix A. Technology matching

Table A1
Matching between the electricity generation technologies in the ESM and the pLCI database, including a description of modifications and weighting.

<table>
<tr><th>Technology name in the ESM ‘ISAaR’</th><th>Process name in the pLCI database</th><th>Data-base region</th><th>Modification / Weighting</th></tr>
<tr><td>PV Open Ground</td><td>electricity production, photovoltaic, open-ground installation</td><td>GER</td><td rowspan="2">Values applied by Hengstler et al. [32], with the following assumptions:
<table>
<tr><td>Module type</td><td></td><td>Mono c-Si</td><td>Multi c-Si</td><td>CdTe</td><td>CIGS</td></tr>
<tr><td>Solar radiation</td><td></td><td>1,200 kWh/(m^2*a)</td><td></td><td></td><td></td></tr>
<tr><td>Market share</td><td></td><td>52.3%</td><td>42.8%</td><td>2.5%</td><td>2.5%</td></tr>
<tr><td>Module efficiency</td><td>18%</td><td>16.8%</td><td>15.3%</td><td>14.6%</td><td></td></tr>
<tr><td>Perfor-mance ratio</td><td>Open Ground</td><td>0.8</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Rooftop</td><td>0.75</td><td></td><td></td><td></td></tr>
<tr><td>GWP100a in gCO$_2$e/kWh</td><td>Open Ground</td><td>57.3</td><td>44.7</td><td>20.2</td><td>33.7</td></tr>
<tr><td></td><td>Rooftop</td><td>53.9</td><td>42.3</td><td>19.6</td><td>32.5</td></tr>
</table></td></tr>
<tr><td>PV Rooftop</td><td>electricity production, photovoltaic, slanted-roof installation</td><td>GER</td></tr>
<tr><td>Nuclear</td><td>electricity production, nuclear, boiling water reactor</td><td>GER</td><td></td></tr>
<tr><td rowspan="2">Biomass-CHP</td><td>heat and power co-generation, biogas, gas engine</td><td>GER</td><td rowspan="2">Technology weighting applied: 2025–2045: a) 73%, b) 27%</td></tr>
<tr><td>heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014</td><td>GER</td></tr>
<tr><td>Lignite</td><td>electricity production, lignite</td><td>GER</td><td></td></tr>
<tr><td>Gas Turbine</td><td>electricity production, natural gas, conventional power plant</td><td>GER</td><td></td></tr>
<tr><td>Geothermal</td><td>electricity production, deep geothermal</td><td>GER</td><td></td></tr>
<tr><td>Gas and Steam</td><td>electricity production, natural gas, combined cycle power plant</td><td>GER</td><td></td></tr>
<tr><td>Run-of-River Hydro</td><td>electricity production, hydro, run-of-river</td><td>GER</td><td></td></tr>
<tr><td>Reservoir Hydro</td><td>electricity production, hydro, reservoir, non-alpine region</td><td>GER</td><td></td></tr>
<tr><td>Oil</td><td>electricity production, oil</td><td>GER</td><td></td></tr>
<tr><td>Hard Coal</td><td>electricity production, hard coal</td><td>GER</td><td></td></tr>
<tr><td>Wind Onshore, Wind Offshore</td><td>electricity production, wind, 1–3 MW turbine</td><td>GER</td><td>Technology weighting applied: 2025: a) 100% 2030, 2035: a) 60%, b) 40% 2040: a) 30%, b) 70% 2045: a) 20%, b) 80%</td></tr>
</table>

(*continued on next page*)

Table A1 (*continued*)

Technology name in the ESM 'ISAaR'	Process name in the pLCI database	Data-base region	Modification / Weighting
	electricity production, wind, >3 MW turbine	GER	
Hard Coal CHP	heat and power co-generation, hard coal	GER	
Lignite CHP	heat and power co-generation, lignite	GER	
Gas and Steam CHP	heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical	GER	
Gas Turbine CHP	heat and power co-generation, natural gas, conventional power plant, 100 MW electrical	GER	
Gas Turbine – Green (Hydrogen)	electricity production, H2, conventional power plant	EUR	Plant: Ecoinvent 3.8; Fuel: hydrogen production, gaseous, 25 bar, from electrolysis; Replaced 0.2629 m^3 natural gas, high pressure (0.85 kg/m^3, LHV, 47.4 MJ/kg with 0.08 kg hydrogen, efficiency 39.8% [ecoinvent]
Gas Turbine – Green (Methane)	electricity production, synthetic methane, conventional power plant	EUR	Plant: Ecoinvent 3.8; Fuel: "synthetic methane" (SNG) = methane, from electrochemical methanation, with carbon from atmospheric CO2 capture, using heat pump heat; Replaced 0.26 m^3 natural gas, high pressure (0.85 kg/m^3, LHV, 47.4 MJ/kg with 0.22 kg SNG (LHV 50.2), [ecoinvent, Zhang et al. [78]]
Gas and Steam – Green (Methane)	electricity production, from CC plant, synthetic methane, no CCS	EUR	Plant: Premise; Fuel: 100% SNG, burned in CC plant, truck 25 km, no CCS; 5.81 MJ SNG / kWhel ≙ 62% plant efficiency [Ecoinvent, Volkart et al. [70], Zhang et al. [78]]
Oil – Green	electricity production, synthetic diesel, conventional oil power plant	EUR	Plant: Ecoinvent 3.8; Fuel: Diesel production, synthetic, Fischer Tropsch process, hydrogen from electrolysis, energy allocation; Replaced 0.23 kg heavy fuel oil (LHV, 39 MJ/kg with 0.21 kg Syndiesel (LHV 42.6 MJ/kg) [Ecoinvent, van der Giesen et al. [68]]
Gas and Steam CHP – Green	heat and power co-generation, synthetic methane, combined cycle power plant, 400 MW electrical	EUR	Plant: Ecoinvent 3.8; Fuel: methane, from electrochemical methanation, with carbon from atmospheric CO2 capture, using heat pump heat; Replaced 0.16 m^3 natural gas, high pressure (0.8 kg/m^3, LHV, 47.4 MJ/kg with 0.12 kg SNG (LHV 50.2), [ecoinvent, Zhang et al. [78]]
Gas Turbine CHP – Green	heat and power co-generation, synthetic methane, conventional power plant, 100 MW electrical	EUR	Plant: Ecoinvent 3.8; Fuel: methane, from electrochemical methanation, with carbon from atmospheric CO2 capture, using heat pump heat; Replaced 0.21 m^3 natural gas, high pressure (0.8 kg/m^3, LHV, 47.4 MJ/kg with 0.16 kg SNG (LHV 50.2), [ecoinvent, Zhang et al. [78]]

Appendix B. Supplementary data

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Green light for bidirectional charging? Unveiling grid repercussions and life cycle impacts

Daniela Wohlschlager [a,b,*], Janis Reinhard [b], Iris Stierlen [c], Anika Neitz-Regett [b], Magnus Fröhling [a]

[a] Chair of Circular Economy and Sustainability Assessment, Technical University of Munich (TUM), TUM Campus Straubing, Am Essigberg 3, 94315 Straubing
[b] Forschungsstelle für Energiewirtschaft (FfE), Am Blütenanger 71, 80995 München
[c] School of Life Sciences, Technical University of Munich (TUM), Alte Akademie 8, 85354 Freising

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ABSTRACT

Bidirectional charging, such as Vehicle-to-Grid, is increasingly seen as a way to integrate the growing number of battery electric vehicles into the energy system. The electrical storage capacity in the system can be enhanced by using electric vehicles as flexible storage units. However, large-scale applications of Vehicle-to-Grid may require significant expansion of distribution grids. Previous studies lack a comprehensive environmental assessment of related impacts. Contributing to this research gap, this article combines techno-economic grid simulations with scenario-based Life Cycle Assessments. The case study focuses on rural distribution grids in Southern Germany, projecting the repercussions of different charging scenarios by 2040. Besides a Vehicle-to-Grid scenario, a mixed scenario of Vehicle-to-Home, Vehicle-to-Grid, and direct charging is investigated. Results indicate that Vehicle-to-Grid charging increases grid impacts due to higher charging simultaneities and power losses, especially when following spot market prices. Despite these challenges, the secondary use of battery electric vehicles as storage units can offset adverse environmental effects. Bidirectional charging allows for higher use of volatile renewable energies and can accelerate their integration into the power system. When considering these diverse environmental effects, bidirectional charging scenarios show overall lower impacts on climate change per battery electric vehicle compared to direct charging. The insights provided are valuable for researchers, industry, utilities, and policymakers to understand the potential positive and negative impacts of large-scale battery electric vehicle integration. The article highlights the most influential parameters that should be considered before large-scale penetration.

1. Introduction

Besides efforts towards a more sustainable modal split, policymakers recognized the switch from internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs) as a vital component to decrease the greenhouse gas (GHG) emissions of the global transport sector [1]. Germany's national targets aim towards a diffusion of 15 million BEVs in Germany by 2030 [2]. To enable an efficient technical and economic integration of BEVs into the energy system, industry, policymakers, and academia have continuously investigated optimized charging strategies, also known as 'smart charging.' [3,4]. This includes unidirectional charging, which optimizes the point of time and duration. In addition, bidirectional charging or vehicle-to-X (V2X) allows the discharge of electricity and thus uses the batteries of BEVs as flexible storage units within the energy system. As outlined in a review by Pearre and Ribberink [3], there is an ongoing development of use cases of V2X, e.g., increased self-consumption in combination with photovoltaic (PV) systems for households (vehicle-to-home, V2H), or commercial buildings (vehicle-to-business or vehicle-to-building, V2B). Cost-optimized vehicle-to-grid concepts (V2G), known as time arbitrage, market- or tariff-optimized charging, allow to charge and discharge based on the spot market price (day-ahead and intraday) [5].

Bidirectional charging concepts require an infrastructure based on information and communication technology (ICT). Literature on environmental assessments of ICT highlights the occurrence of 'first-order' and 'higher-order' effects [6]. Accordingly, 'first-order' effects include impacts on the 'technology level' and, thus, the impact caused by ICT components, typically determined through the standardized Life Cycle

* Corresponding author.
E-mail address: daniela.wohlschlager@tum.de (D. Wohlschlager).

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Assessment (LCA). For example, ICT charging infrastructure for bidirectional charging can lead to a higher environmental footprint than conventional chargers due to the additional required power electronics [7,8]. The definition of 'higher-order' effects includes systemic consequences, i.e., effects on the 'system level,' caused by a large-scale diffusion of ICT-based products or services [6]. Scholars assessing ICT have discussed potential environmental effects on the overall economy or society (cf. review by Horner et al. [9]). Investigations on the environmental consequences of ICT-enabled use cases, specifically in smart energy systems (SES), typically combine the methods of techno-economic energy system modeling and LCA (cf. Wohlschlager et al. [10]). Investigations on the impacts of BEV charging strategies on the power sector, e.g., with a global [11], European [12], or national [13] scale, conclude on reduced overall emissions in the system. This results from shifting charging into hours with a high RE-share in electricity generation, while discharging leads to a substitution of fossil-based generation. A prospective LCA (pLCA) approach has been developed to evaluate the impacts of such emerging use cases in a future scenario. By definition, a pLCA assesses a product system that – at the time of the study – lies in the future [14]. Besides using scenarios, this involves a modification of the Life Cycle Inventory (LCI) to consider future developments in the LCA [15].

Next to the potential emission reductions on an energy system level, additional load caused by BEVs can burden the grid infrastructure. Gemassmer et al. [16] investigate cost-optimized unidirectional charging in future scenarios in Germany. Although the authors conclude there is potential to balance generation from volatile RE and the consumption from the increasing amount of BEVs, it causes significant grid overloads. Similarly, Müller et al. [17] show higher peak loads in low-voltage grids in the case of a large-scale application of cost-optimized V2G charging compared to direct (uncontrolled) charging. Both studies recommend a more balanced charging strategy, including considering the local grid situation. While these studies have focused on the techno-economic implications of V2G charging on distribution grid infrastructures, they lack an environmental assessment of respective grid reinforcement requirements. A few LCA studies focused on electricity grid infrastructures. For example, Jorge and Hertwich [18] assessed scenarios of expanding the European transmission grid, while Itten et al. [19] and Jorge et al. [20,21] investigated grid components, including those on the distribution grid level. However, to the author's knowledge, environmental assessments on grid reinforcement requirements depending on the charging strategy of BEVs pose a research gap. Secondly, the environmental impacts on the system level need to be compared to other consequences or potential impact reductions caused by smart charging strategies. This includes impacts caused on the technology level, such as the footprint of required ICT or the changing operational impact of BEVs, typically determined for the climate change impact category [22].

Overall, this article's aim and scientific contribution is to provide a methodological and empirical foundation to enhance the understanding of environmental effects associated with a large-scale implementation of bidirectional charging. First, we add insights into the systemic long-term repercussions caused within distribution grids and the research gap on the associated prospective life-cycle impacts. Secondly, we provide a larger picture of the environmental effects of bidirectional charging by comparing the effects on the distribution grid to other consequences on the system and technology levels. To reach these goals, we answer the following research questions:

1. *What are the prospective life-cycle environmental effects caused by repercussions within distribution grids resulting from a high penetration rate of bidirectional charging strategies?*
2. *Compared to other environmental effects due to bidirectional charging, what is the magnitude of these systemic impacts on distribution grids?*

For elaboration, we develop and outline the methodological steps to combine techno-economic modeling and a pLCA. Enhanced with empirically collected LCI data, this article provides a blueprint for LCA researchers and professionals to determine the future systemic effects within distribution grids and on the technology level. The novel methodological contribution can be transferred to assess other geographical scopes or use cases in SES. We investigate the repercussions within the distribution grid for three different charging strategy scenarios. The grid simulation results provide insights for utilities and distribution system operators (DSOs) on the long-term grid expansion requirements in case of a large-scale diffusion of BEVs and how bidirectional charging strategies can influence these. The novelty lies in the environmental assessment and comparison of these effects to the consequences of bidirectional charging on the footprint of required ICT and changing operational emissions of BEVs. Lastly, we reflect on possible impacts on overall power generation. LCA results provide novel insights for researchers, industry, and political decision-makers on expected future environmental implications on different levels and the most sensitive parameters.

The relevance of this article lies in the methodological contribution to determining a holistic picture of environmental effects associated with novel use cases in SES. Furthermore, this research bridges the gap between technological advancements and practical implementation, addressing critical challenges for large-scale integration of bidirectional charging. This study contributes to the broader discourse on sustainable energy transitions.

Regarding the scope of this article, the assessment is concerned with environmental impacts only. The economic revenue potentials of bidirectional charging have been assessed continuously in the literature, as shown in a review by Dossow and Kern [23]. Furthermore, this article aims to investigate the impacts caused by a large-scale diffusion of battery electric vehicles. We thus focus on the effects by 2040. Determining the path towards that, e.g., annual grid expansion needs, would require detailed data and information on local expansion plans, which is beyond the aim and scope of this study.

Section 2 outlines the methodological approach of the study, structured along the four steps of an LCA. Section 3 summarizes empirical findings, followed by a discussion and critical reflection in Section 4. The article closes with recommendations for future assessments in Section 5.

2. Methods

Fig. 1 depicts the methodological approach to quantify the systemic effects of bidirectional charging strategies on distribution grids. Applying an LCA in line with the ISO 14040 and 14044, the following sections specify the steps of the four phases, including the goal and scope definition (Section 2.1), the inventory analysis (Section 2.2), the impact assessment (Section 2.3), and interpretation of the results (Section 2.4).

2.1. Goal and scope definition

This comparative pLCA aims to quantify prospective environmental impacts from reinforcement requirements in the distribution grid caused by implementing BEVs depending on the charging strategy in the year 2040. We conduct a case study for a rural distribution grid area in Bavaria, Southern Germany. Data on 1,206 real low-voltage grids as of 2020, obtained from Bavaria's largest DSO (Bayernwerk Netz GmbH), serve as a starting point for the simulation (see Section 2.2.1). The year 2040 is the future scenario in this case study, assuming a high penetration of BEVs in Germany according to the governmental targets. To interpret the systemic effects determined within the distribution grid, we compare the impacts to those caused on the technology level. Hereby, we consider two aspects influenced by the charging strategy in a pLCA: the operational emissions of BEVs and the required ICT for the charging infrastructure. In addition, we discuss how these impacts compare to the effects on electricity generation emissions in the entire

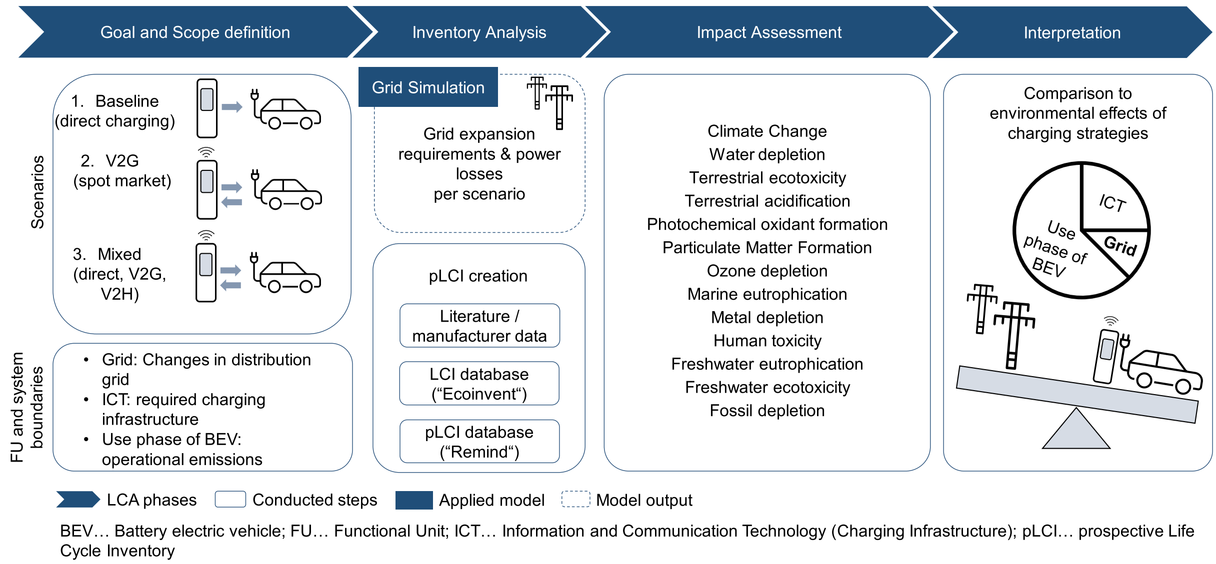

Fig. 1. Methodological approach of the LCA to quantify the systemic effects of charging strategies on distribution grids.

power system based on previous assessments (Section 4). The following sections outline the specifications of the assessed scenarios, the functional unit, and system boundaries.

2.1.1. Scenarios

To determine the respective grid reinforcement requirements from 2020 to 2040 depending on the charging strategy of BEVs, we analyze three scenarios (see Table 1). Each scenario applies different use cases of charging, resulting in different expansion requirements of the modeled low-voltage grids by 2040. Details on implementing BEVs and charging strategies in the grid simulation model are outlined in Müller et al. [17]. While the predicted penetration of electrical consumers (e.g., heat pumps) and producers (e.g., PV systems) in the modeled distribution grid area remains equal among all scenarios, the charging strategy or the mix of charging strategies of BEVs differs. The comparative pLCA thus allows us to determine the effects in the distribution grid entirely attributable to the respective charging strategy. The following sections outline the investigated scenarios.

2.1.1.1. 'Baseline' scenario. The 'Baseline' scenario serves as a reference case. Regarding the charging strategy, 100 % of the BEVs apply direct charging by 2040. When a vehicle returns to the charging station from a trip, it is plugged in and starts charging at maximum power until it is fully charged or the next journey begins. There is no possibility of discharging electricity to the grid.

2.1.1.2. 'V2G' scenario. In the 'V2G' scenario, 100 % of the BEVs apply bidirectional charging based on the spot market price, i.e., charging at low prices and discharging back into the distribution grid at high electricity prices. Due to the expected correlation between GHG emissions and electricity prices, previous investigations such as Fattler [24] and Xu et al. [12] determine high environmental benefits in the use phase of BEVs when applying V2G charging. Although this scenario represents an extreme case, we investigate whether significant repercussions on distribution grids (see Müller et al. [17]) are counterproductive for reducing GHG emissions of BEV operation. The comparison is presented to interpret the results in Section 3.4.

2.1.1.3. 'Mixed' scenario. Blume et al. (2022) describe the 'Mixed' scenario. Accordingly, the scenario aims to represent a more realistic case than the 'Baseline' and 'V2G' scenarios by including a mix of different charging strategies. The percentual share per charging strategy was determined in stakeholder workshops as part of the 'BCM - Bidirectional Charging Management' research project.[1] The actors involved in the iterative process include original equipment manufacturers (OEMs) from the automotive industry, charging infrastructure and software suppliers, and distribution and transmission system operators (DSOs and TSOs). The iterative stakeholder process followed a multi-stage approach where stakeholders were individually interviewed on an assumed percentual distribution of charging strategies by 2040. In the first round, each stakeholder participated independently in separate discussions. At the end of this round, the assumptions were synthesized, resulting in a consolidated value agreed on in the second round. As displayed in Table 1, the resulting 'Mixed' scenario assumes a share of 17 % of BEVs applying V2G charging based on the spot market price. In addition, 19 % follow a charging strategy to increase self-consumption with a PV system comparable to a conventional home storage system, also known as V2H charging. In this case, the BEV charges in times of an electricity surplus from PV production and discharges when the household's demand exceeds the PV production. The remaining share in the 'Mixed' scenario charges directly. As outlined in the following section, resulting grid expansion requirements per scenario serve as the starting point for the LCA.

2.1.2. Functional unit and system boundaries

After determining the effects on the system level, i.e., repercussions within the distribution grid, we compare those to the impacts on the technology level. For the latter, we include two aspects that are influenced by the charging strategy, while the vehicles and, thus, their production footprint are assumed to be equal between the scenarios. Accordingly, the changing operational emissions of BEVs and the

Table 1
Overview of use cases per modeled scenario in the simulation by 2040.

	Scenario (share of BEVs applied)		
Charging strategy (optimization)	Baseline	V2G	Mixed
Direct	100 %	–	64 %
V2G (spot market price)	–	100 %	17 %
V2H (increasing self-consumption)	–	–	19 %

[1] Supported by the German Federal Ministry for Economic Affairs and Climate Action, Grant No. 01MV18004F

required ICT per charging strategy are investigated. The functional unit (FU) for each perspective is outlined as follows.

2.1.2.4. System level. Regarding systemic repercussions, the FU comprises the difference of grid expansion requirements within the investigated grid area by 2040 between the scenarios. The 'Baseline' scenario, i.e., a scenario with direct charging, serves as a reference. The system boundaries cover the difference in grid expansion requirements of the 'Baseline' ($e_{baseline}$) compared to requirements resulting in the 'V2G' (e_{V2G}) and 'Mixed' (e_{mixed}) scenarios respectively. The differences between the scenarios (Δe) are determined as followed:

$$LCA_{V2G} = \Delta e_{V2G,baseline} = e_{V2G} - e_{baseline}$$

$$LCA_{mixed} = \Delta e_{mixed,baseline} = e_{mixed} - e_{baseline}$$

As illustrated in Fig. 2, e consists of three elements: changes in the total length of grid lines, units of replaced transformers, and annual power losses within the total grid after expansion in 2040. To determine the yearly values of e for the expansion requirements in 2040, the article uses an average annual value based on the difference of the total grid length of 2020 and 2040 as determined with the grid simulation. We thus divide the total net changes by 20 years to determine the annual values of e. Changes besides the integration of BEVs are attributable to the penetration of diverse other electrical consumers and producers (cf. Section 2.1.1). Since these other developments remain equal among the scenarios, the determined differences $\Delta e_{V2G,baseline}$ and $\Delta e_{mixed,baseline}$ represent the changes attributable to the charging strategy of BEVs.

Regarding the geographical scope, we conduct the case study for rural electricity grids distributed throughout Bavaria, Germany, and consider national targets for the diffusion of BEVs. We follow a cradle-to-grave approach and thus include the production, operation, and end-of-life phases. Environmental impacts in the production stage of the grid lines and transformers arise due to the sourcing and processing of raw materials, the manufacturing processes, the transportation, and the installation. The operation phase encompasses the power losses from transformers and grid lines within the grid area. We exclude maintenance measures due to the marginal maintenance requirements of grid lines [20] and transformers [21]. We assume a lifetime of 40 years for grid lines and 35 years for transformers, following the usual lifetimes of components in the German distribution network (StromNEV Annex 1 to Section 6 (5) Sentence 1). We thus adjust the resulting transformer replacements with the factor 1.14 (40/35) for the LCA. The end-of-life stage includes the deconstruction of the cable and the disposal and recycling of the transformer or cable components. Following the European Commission JCR (2011) recommendation, we chose the allocation approach 'cut-off,' i.e., the primary producer receives no credit for providing recyclable materials.

2.1.2.5. Technology level. For the operational emissions per BEV, the FU covers the annual electricity for charging and discharging for operation in Germany in the case of bidirectional charging. Emissions are quantified through the intersection of the hourly volumes of (dis-)charged electricity with the respective hourly emission factor of electricity generation (EMF). In line with the method by Fattler [24], emissions in hours of discharging enter the balance with a negative sign, assuming a substitution of electricity generation from other power plants in the electricity system. The allocation thus follows the approach of 'system expansion' by considering the secondary purpose of BEVs as a flexible storage unit for the energy system.

The FU for ICT encompasses the infrastructure required for private charging of one BEV per year. Following the LCA for charging infrastructure as applied in Germany conducted by Wohlschlager et al. [7], considered components include a wallbox and intelligent metering infrastructure (iMSys). For differences in the wallbox, the study assumes an alternating current (AC) wallbox for direct charging and a direct-current (DC) wallbox for bidirectional charging (see Section 2.2.3).

2.2. Inventory analysis

Following the defined system boundaries, the grid expansion requirements per scenario are determined with the simulation model 'GridSim.' This section briefly introduces the applied simulation model, followed by the information collected on the material compositions and adjustments in the LCI database.

2.2.1. Grid simulation

'GridSim' is a techno-economic model for analyzing distribution grids (details in [25]). The scope of the simulation encompasses 1,206 rural low-voltage grids located throughout Bavaria, Germany, with an initial grid length of 3,016 km and 1,206 transformers (details see [17]). This represents 0.3 % of the circuit length of Germany's low-voltage grid, which has a length of 1.2 mio. km as of 2023 [26]. These grids consist of underground cables to a considerable extent, and overhead lines are rare. The modeled components in the low-voltage grids include households, commercial units, heat pumps, electric storage heaters, PV systems, and stationary battery energy storage systems (BESS). The households' electric load, heating, and mobility demand are consistently modeled with individual profiles using a statistical model described by Müller et al. [27]. As outlined in Müller et al. [17], the assumptions for the future penetration of BEVs within the grid are based on the 'solidEU' scenario [28]. The regionalization follows the Scenario 2035 B of the German Network Development Plan [29]. 'solidEU' represents an European climate-policy scenario modeled with the energy system model (ESM) 'ISAaR' for each European country. The model represents a linear optimization multi-ESM minimizing the total costs of the system (model landscape outlined by Kigle et al. [30]). As the applied ESM was part of the original modeling landscape when developing 'solidEU,' it enabled a coherent update that specifically concerned the implementation of bidirectional charging. Applied spot market prices for charging and the remuneration for discharging are derived from the updated scenario. Table 2 displays the specifications regarding the technical parameters for BEVs as considered in the grid simulation.

The simulation synthesizes BEV load profiles depending on the presence of the vehicles at the charge points and their energy demand. In the reference case, BEVs immediately start charging when plugged in (direct charging). In the case of bidirectional charging, the load profiles result from a linear cost optimization problem, i.e., charging and discharging based on spot market prices (V2G) or optimized on PV self-consumption (V2H) [17]. After calculating the residual load at each grid connection point (GCP), the load of all components is considered, and load flow calculations are carried out.

The model assumes a grid overloaded when the voltage at the GCPs violates a $\pm$ 6 %[2] band around nominal voltage or if the nominal current of a line or transformer exceeds 100 % of its rated current for at least one 15-minute time step (details in Blume et al. [31]). The model solves voltage band violations and overloaded lines through additional lines parallel to the existing ones. Transformer overloads lead to a replacement with one of a higher rating power. The remaining network congestion is iteratively tracked and evaluated until all critical situations are resolved.

2.2.2. Life cycle inventory of grid components

Sources for obtaining the LCI of distribution grid components, such as transformers or grid lines, are scarce. For instance, the comprehensive

[2] The DIN VDE 50160 standard allows 10 % voltage deviation. This deviation is reduced to 6 % because the simulation only considers the voltage drop at the substation transformer and the lines in the low voltage. Of share of 4% maximum voltage drop is assumed for the superimposed medium voltage grid.

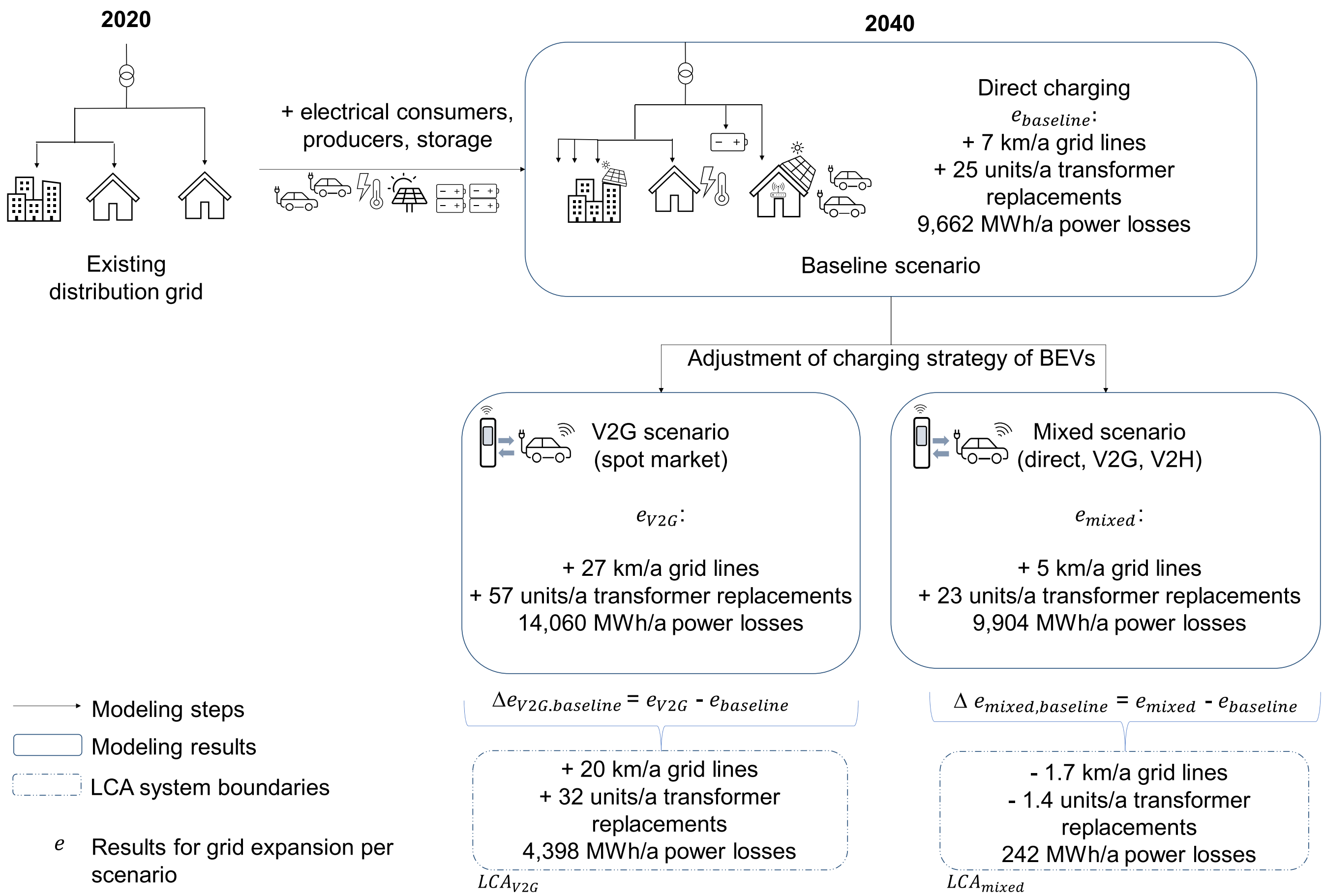

Fig. 2. System boundaries of the LCA on effects on the distribution grid per charging strategy.

Table 2
Technical specifications of BEVs assumed in the simulation by 2040 [17,25].

Parameter [unit]	Input value
Battery capacity [kWh] (proportion in the fleet)	38 (27.6 %), 60 (40,6 %), 100 (31.8 %)
Plug-in-probability [%]	100
Average annual mileage per vehicle [km]	10,730
Charging (or discharging) power [kW]	11
Charging (or discharging) efficiency [%]	94
Minimum battery State-Of-Charge at departure [%]	70
Minimum battery State-Of-Charge security [%]	30

LCA database Ecoinvent only provides the grid's total impact (for distribution grids, e.g., with the process 'distribution network, electricity, low voltage'). Assigning emissions or input flows to individual grid components is impossible. By conducting a literature review, we determine four studies that contribute to the LCI of this study: Jorge and Hertwich [18] focus on evaluating future grid expansion scenarios. We derive LCI data on recycling and manufacturing processes. A report by Itten et al. [19] investigates the environmental impact of global electricity production and distribution, providing assumptions for the life cycle phases of installation, deconstruction, and disposal or recycling used in this article. Thirdly, Jorge et al. [20,21] assess the impact of grid lines and transformers, respectively, including LCI data on those applied at low-voltage levels and assumptions on recycling and disposal rates. Using existing literature on these established components of distribution grids as a starting point, we supplement the LCI with data from grid simulations and recent manufacturer datasheets.

To conduct a pLCA, we apply the Python extension 'premise' outlined in Sacchi et al. [32] to transform the LCI database Ecoinvent 3.8 into a prospective database for the year 2040. 'premise' considers global future scenarios from a chosen Integrated Assessment Model (IAM), using so-called 'shared socioeconomic pathways' (SSPs) to project global consequences including GHG emissions and climate impacts (see Riahi et al. [33]). In line with the underlying climate targets of the grid simulation in this article, we choose the scenario 'SSP2-PkBudg1150' of the IAM 'remind' [34]. This scenario considers business-as-usual trends, aiming to keep global warming below 2°C, thus restricting cumulative emissions to a budget of 1150 $GtCO_2$.

In line with the geographical scope of the use case, we apply the electricity mix determined for Germany for power losses (see below 'Operation'). For production processes, e.g., raw material sourcing that occurs in other parts of the world, or if no country-specific data is available, we use European (RER) or global (GLO) data sets as a proxy [35]. The following sections outline the data for each phase of the LCA in this study, following the norms of ISO 14040 and ISO/TR 14049:2012. The following sections outline details on modeled components and data collection for each life cycle phase.

2.2.3. Raw materials

Cables used for grid line expansion are all of the same type in the simulation: A three-phase aluminum cable with a diameter of 240 mm^2 and roughly 360 amps rated current (cable type NAYY-J 4 × 240 SE) in line with the norm for distribution cables [36]. Values on the weight composition stem from the data sheet of Klaus Faber AG [37]. The most applied type for transformer replacements is a three-phase, ground--mounted, oil-immersed distribution transformer with a rated power of 630 kVA. For simplification, we thus assume the size of 630 kVA for all transformer replacements. As the technical specifications and losses align with those in the grid simulation, we model the type 'TUMETIC' from 39 with 20 kV rated voltage, 4 % impedance voltage, and the highest efficiency class (C—C' combination as specified in the norm DIN 42500). The available technical report [38] includes information on total weight, while we obtained the shares of material compositions from the manufacturer. Table A.1 in the Appendix outlines the material composition, including the chosen process name of the Ecoinvent database.

2.2.4. Manufacturing and transport

For manufacturing, we model 2.1 kWh of electricity and 0.01 m^3 of natural gas demand per kg of aluminum for the cable [18,39]. For the transformers, we model an energy input of 0.47 kWh of electricity and 0.19 m^3 natural gas per kVA and the emissions resulting from the manufacturing process [21]. We derive the values on transport distances from Frischknecht et al. [40] for cables and Jorge et al. [21] for transformers.

2.2.5. Installation and deconstruction

According to Itten et al. [19], we assume an excavation volume of 30 m^3 per kilometer of grid line installation and deconstruction. Following Itten et al. [19] and Jones and McManus [41], the cable duct consists of plastics and resin in 70 % of the cases, with the remaining 30 % combining steel and concrete. We further apply a deconstruction rate of 80 % for grid lines, while 20 % remain underground [19]. Due to the comparatively marginal impacts shown by Itten et al. [19], we exclude the installation and deconstruction phase of the transformers.

2.2.6. Operation

The impact during the operation phase reflects the power losses in the grid lines and transformers multiplied by the national average EMF by 2040. The EMF is determined following the pLCA approach outlined in Wohlschlager et al. [13]. For consistency, we apply the method of electricity generation resulting from the ESM 'ISAaR' as used in the grid simulation (see Section 2.2.1) and the pLCI database modified with 'premise' (see Section 2.2). Since the system boundaries of our LCA are within a sample of distribution grids rather than on a national scope (see Section 2.1.2), we do not consider repercussions from the charging strategies on the national electricity sector. The resulting annual average EMF of 46 gCO_2-eq./kWh by 2040 thus applies to all investigated scenarios ('Baseline,' 'V2G', 'Mixed').

2.2.7. Recycling/Disposal

Based on Jorge and Hertwich [18], we apply a recycling rate of 90 % for all metal components and assume deposition in a landfill for the remaining components (concrete, gravel, transformer oil, etc.). The recovery options for scrap metals for grid lines must be explicitly evaluated concerning their use as electrical conductors. Grimaud et al. [42] explain that aluminum used for electricity grid lines has high purity requirements (99.7 %) to achieve optimum electrical conductivity. Since secondary aluminum typically does not meet these quality requirements, aluminum conductors in this study are assumed to be made exclusively from primary raw materials, and their recycling means downcycling.

2.2.8. Life cycle inventory of BEV operation and ICT

For the LCI of ICT and BEV operation, we build upon literature. For consistency and comparability, specifications on the investigated BEV, e.g., annual mileage and battery capacity, equal those outlined in Table 2. Furthermore, we apply equal pLCI databases and scenario assumptions to evaluate grid expansion (Section 2.2.2). The LCI data is collected as follows:

2.2.8.6. Operational emissions of BEVs. Data on the charging profiles and hourly electricity generation result from the grid simulations and the energy system model 'ISAaR.' We use the average life-cycle emission factors per hour, determined according to the method outlined in Wohlschlager et al. [13].

2.2.8.7. ICT for charging infrastructure. Data on required ICT for V2G, V1G, and direct charging is provided in a previous comparative LCA for direct and V2G charging [7]. Using inventory data outlined in Wohlschlager et al. [7], we re-calculate the impact according to the pLCA approach in this study. For the operation phase of ICT by 2040, we use average hours of (dis-)charging per BEV resulting from the grid simulation per scenario (see Appendix, Table A.2).

2.3. Impact assessment

After setting up the LCI, we translate input and output flows into their potential environmental impact using the open-source software 'Brightway2' (see Mutel [43]). Following the research objective and relevant literature, climate change (GWP 100) is the main impact category using the 'IPCC 2013 no LT' method. The comparative assessment of impacts on the technology level (operation of BEVs and required ICT) is limited to climate change as the most applied impact category for analyzing BEVs [22]. The systemic effects caused by grid expansion are further investigated for other environmental impacts. We assess the chosen impact categories of the 'ReCiPe Midpoint (H) V 1.13 no LT' method. Exemptions from the assessment are marine ecotoxicity, involving a high degree of uncertainty [20], and ionizing radiation, which is unsuitable since power grids involve non-ionizing radiation [18].

2.4. Interpretation

We first outline the total annual impacts of distribution grid expansion by 2040 to evaluate the results. Exemplarily discussed for LCA_{V2G} (difference of 'Baseline' to 'V2G' scenario), this includes the total values per impact category along with the contribution per component and life cycle phases (Section 3.2). For identified most contributing life-cycle stages, we follow the guidelines of the European Commission JCR [44] by applying a sensitivity analysis (Section 3.3).

Next, we interpret the magnitude of determined systemic effects through a comparison to other environmental effects of bidirectional charging. This includes an investigation of the changing impacts on the technology level, i.e., per BEV. Hereby, we compare the systemic effects of grid expansion to the operational emissions of BEVs and the required ICT per charging strategy (Section 3.4). As part of the discussion in Section 4, we reflect on our quantified results by including the perspective of effects on the entire power system.

3. Results

To elaborate on the first research question, we show the systemic effects on the distribution grid per scenario. A contribution analysis on the impact shares per component and life-cycle stage is outlined for the 'V2G' scenario (Section 3.2). This is followed by the sensitivity analysis results (Section 3.3). To answer the second research question, we put these systemic effects of the 'V2G' and 'Mixed' scenarios into context. We thus illustrate the systemic effects per BEV compared to the impact caused by ICT and the operation of BEVs per scenario, i.e., charging strategy (Section 3.4).

3.1. Changes in distribution grids per scenario

Table 3 shows the resulting impacts on the grid per scenario for the total expansion of the 20-year time frame (2020 – 2040) and for the LCA reference year 2040. The 'Baseline' scenario results in a 45.6 % share of

Table 3
Simulation results on the grid status and expansion requirements between 2020 - 2040 and annual values for 2040 (e) per scenario.

Scenario	Share of grid overloads (% of total)	Electricity volumes per BEV (charged | discharged kWh/a)	Grid line expansion (km | km a^{-1})	Excavation effort (km | km a^{-1})	Transformer replacements (units | units/a[1])	Power losses[2] (grid lines | transformers MWh/a)
Baseline	45.6	2,362 | -	142 | 7.1	120 | 6	493 | 25	3,791 | 5,871
V2G	71.3	6,875 | 4,006	540 | 27	396 | 20	1,135 | 57	6,095 | 7,965
Mixed	42.7	3,368 | 958	109 | 5.5	96 | 4.8	465 | 23	4,125 | 5,779

[1] Adjusted with the factor 1.14 (40/35) due to the lifetime of 35 years for transformers.
[2] Total power losses in the year 2040 in the investigated grid area after grid expansion.

overloaded grids by 2040, including overloads in grid lines, transformers, and voltage violations (see Section 2.2.1). Regarding the impact of BEV charging, simulations show that evening peaks mainly occur when direct charging is assumed, as many commuters return to their homes at this time and start charging immediately. In the 'V2G' scenario, an overload occurs in 71.3 % of investigated grids. First, this larger share is due to increased simultaneities as the charging processes in the 'V2G' case follow the spot market price signal. Secondly, the increased energy exchange of the BEVs with the grid leads to an increased average grid utilization. While electricity volumes related to charging processes (charging and discharging) amount to 2,362 kWh/a in the 'Baseline' case, the volumes increase by 83 % (total of 4,326 kWh) in the 'Mixed' and even by 361 % (total of 10,880 kWh) in the 'V2G' scenario. For the same reasons, power losses of grid lines in the 'V2G' scenario are almost twice as high as in the 'Baseline' scenario in the resulting grid post-expansion in 2040. Although the 'Mixed' scenario causes slightly fewer grid overloads than the 'Baseline' (42.6 % vs. 45.6 %), power losses in grid lines are higher because of the increased energy exchange of the BEVs with the grid.

Regarding the expansion of grid components, the 'V2G' scenario shows significant increases in both grid line expansion (+280 %) and transformer replacements (+130 %) compared to the 'Baseline' case. In contrast, the 'Mixed' scenario shows lower expansion rates for grid lines (−23 %) and transformer replacements (−6 %) than direct charging. For modeling the operation phase, the difference in power losses post-expansion is an input in the comparative LCA. Although the total power losses (sum of losses in grid lines and transformers) are higher in both scenarios with bidirectional charging strategies, the increase of 3 % in the 'Mixed' scenario is minor compared to the +46 % in the 'V2G' case.

Across all scenarios, Table 3 further shows a lower excavation effort than the kilometers of grid line expansion. This is because some grid lines are added parallel, e.g., within one cable duct, especially in the 'V2G' scenario. We consider the excavation effort for the phases of installation and deconstruction.

The annual values in Table 3 show the expansion requirements considered in the LCA reference year 2040. As outlined in Section 2.1.2, these values refer to the average expansion in the 20-year time frame (2020 – 2040), i.e., total expansion requirements divided by 20 years.

Table 4 outlines the resulting elements considered within the system boundaries for the LCA per scenario, i.e., $\Delta e_{V2G,baseline}$ and $\Delta e_{mixed,baseline}$ (cf. Section 2.1.2). Since we determine the impact in 2040, we consider the annual values within the system boundaries.

Table 4
Difference in grid expansion requirements per scenario compared to the 'Baseline' ($\boldsymbol{\Delta e}$) as considered in the system boundaries of the comparative LCA.

	Grid line expansion (km a^{-1})	Transformer replacements (units/a)	Grid line power losses[1] (MWh/a)	Transformer power losses[1] (MWh/a)
$\boldsymbol{\Delta e_{V2G,baseline}}$	19.9	32.1	2,304	2,094
$\boldsymbol{\Delta e_{mixed,baseline}}$	−1.7	−1.4	334	−92

[1] Values refer to the difference in power losses in the year 2040 in the investigated grid area after grid expansion.

3.2. Systemic effect of bidirectional charging on the distribution grid

Used as an input for the comparison with effects on the technology level, Table 5 shows the impact on climate change (GWP 100) in total and per BEV for the scenarios 'V2G' (LCA_{V2G}) and 'Mixed' (LCA_{mixed}). According to the system boundaries, results represent the difference from the 'Baseline' scenario by 2040. In the case of V2G charging, the additional GWP amounts to 237 tCO_2-eq. in total and 97.8 kgCO_2-eq./BEV by 2040. The 'Mixed' scenario reduces this impact by 97 %, resulting in a plus of 8.3 tCO_2-eq. in total and 3.4 kgCO_2-eq./BEV compared to direct charging.

Resulting values for all impact categories and life-cycle phases are provided in the Appendix for LCA_{V2G} (Table A.3) and LCA_{mixed} (Table A.4).

For a contribution analysis, Fig. 3 exemplarily outlines the results of LCA_{V2G}. In most impact categories, transformer replacements contribute with a slightly higher share compared to grid line expansions (Fig. 3, left side). This is due to the comparatively higher power losses of transformers (see Table 3), representing the operation phase, which is the most impactful life-cycle phase (Fig. 3, right side). Besides the operation phase, raw materials are thus almost entirely responsible for the remaining impacts across all categories. Raw materials dominate the impact categories of human toxicity and metal depletion, with over one-third of the impact share. Following ISO 14040 and 14044 standards, the following section outlines a sensitivity analysis for these two life-cycle phases to determine the reduction potentials of environmental impacts.

3.3. Sensitivity analysis

3.3.1. Operation phase

For the impact caused during the operating phase, i.e., power losses, the GHG intensity of electricity is decisive. The grid simulation uses an average EMF of 46 gCO_2-eq./kWh for the German electricity mix by 2040, resulting from the updated version of the 'solidEU' scenario (see Section 2.2.1). To investigate the sensitivity of the underlying EMF, we model two additional cases: the 'slower defossilization', with 57 gCO_2-eq./kWh (resulting from the scenario 'solidEU,' see Guminski et al. [28]) and the 'ambitious defossilization,' with 25 gCO_2-eq./kWh (resulting

Table 5
Annual impacts (GWP 100) of systemic effects on the distribution grid in total and per BEV for the 'V2G' and 'Mixed' scenarios by 2040, Δ compared to the 'Baseline' scenario.

Annual Climate Change (GWP 100) by 2040 in kgCO_2-eq., **Δ** to 'Baseline'	Impact grid reinforcement/a[1] (2040)	Impact per BEV/a[2] (2040)
$\boldsymbol{LCA_{V2G}}$	237,402	97.8
$\boldsymbol{LCA_{mixed}}$	8331	3.4

[1] Within the grid area considered, consisting of 1206 low-voltage distribution grids in Southern Germany.
[2] The simulation integrates 48,567 BEVs in the investigated grid area and time frame (2020 – 2040). Assuming a linear diffusion, the annual integration is 2428 BEVs.

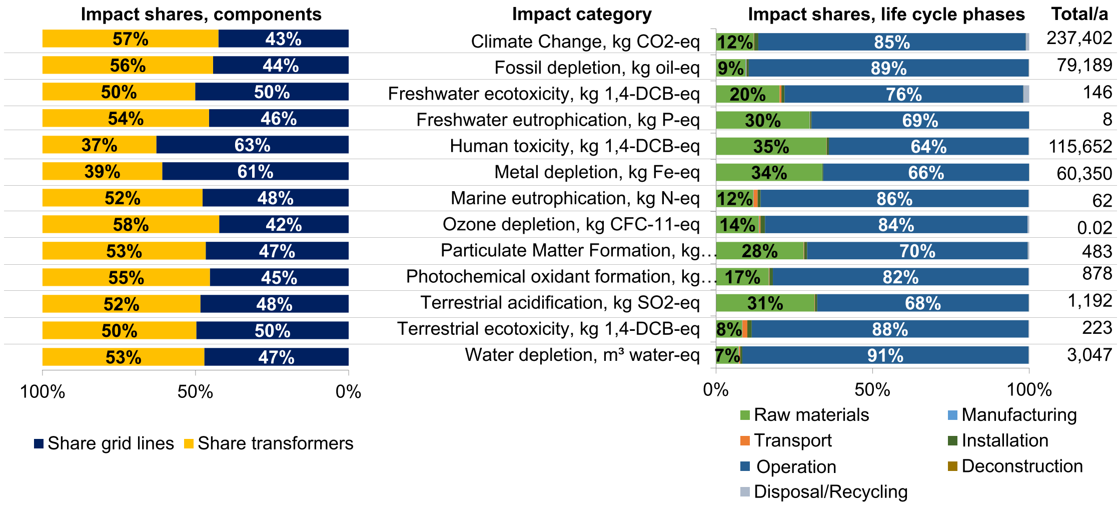

Fig. 3. Shares of annual impacts per component (left) and life cycle phases (right), resulting from LCA_{V2G} (difference of 'V2G' to 'Baseline' scenario).

from the scenario 'V2G', see Wohlschlager et al. [13]). Fig. A.2 in the Appendix depicts the composition of the electricity mix for these three cases.

Fig. 4 shows the impact change per sensitivity scenario compared to the $\boldsymbol{LCA_{V2G}}$ results in the default case (i.e., 46 gCO_2-eq./kWh). Accordingly, a high share of RE in electricity generation in the 'ambitious defossilization' case is most sensitive to the impact categories of fossil depletion (−52 %) and climate change (−39 %). This is because these impact categories are sensitive to the combustion of fossil energy carriers, which decreases in the ambitious case (see Fig. A.2). On the contrary, there are slight increases between 3 and 4 % in several impact categories (see Fig. 4, right side). The raw materials used for RE generation units mainly impact these categories. For example, resulting LCA data indicates that human toxicity impacts primarily result from copper production used in wind turbines. The comparatively higher share of wind energy in the 'ambitious defossilization' case (see Fig. A.2) thus leads to increased impacts. Interestingly, the 'slower defossilization' and thus a lower RE-share leads to the comparatively most significant impact reductions of water depletion (−10 %) and terrestrial ecotoxicity (−8 %). As results show, these impacts primarily occur from silicon production used in PV systems, and the impacts correlate with the share of PV in the electricity mix per sensitivity case (see Fig. A.2).

3.3.2. *Raw materials*

Regarding the life-cycle phase of raw materials, the energy-intensive production of aluminum used for grid line expansion is primarily responsible for the most impact categories. In the initial LCI, we chose primary materials due to the high purity requirements of metals used in grid lines (see Section 2.2.2), which especially applies to aluminum. To investigate the sensitivity of using secondary materials as a future scenario, we model a 25 % and 50 % share of secondary aluminum, respectively. Results in Fig. 5 show the impact changes compared to the base case (primary materials). Analog to Fig. 4 on the sensitivity on the EMF, Fig. 5 includes the changes compared to the total impacts of grid

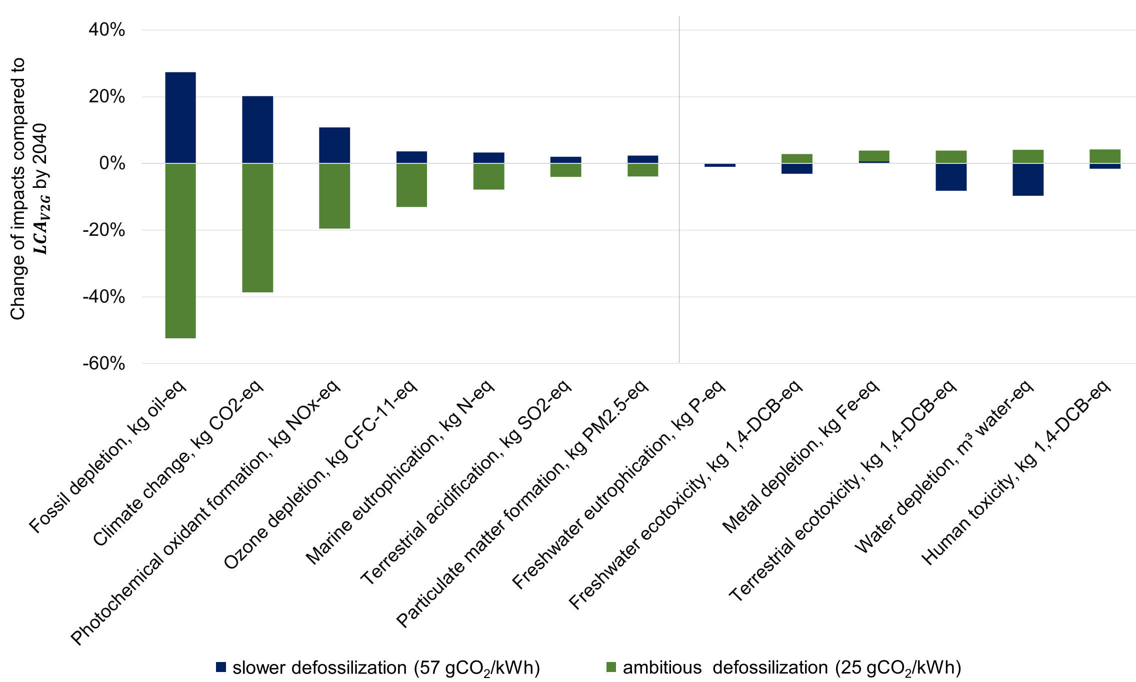

Fig. 4. Change of impacts of grid reinforcement (LCA_{V2G}) by 2040, sensitivity on EMF of national electricity.

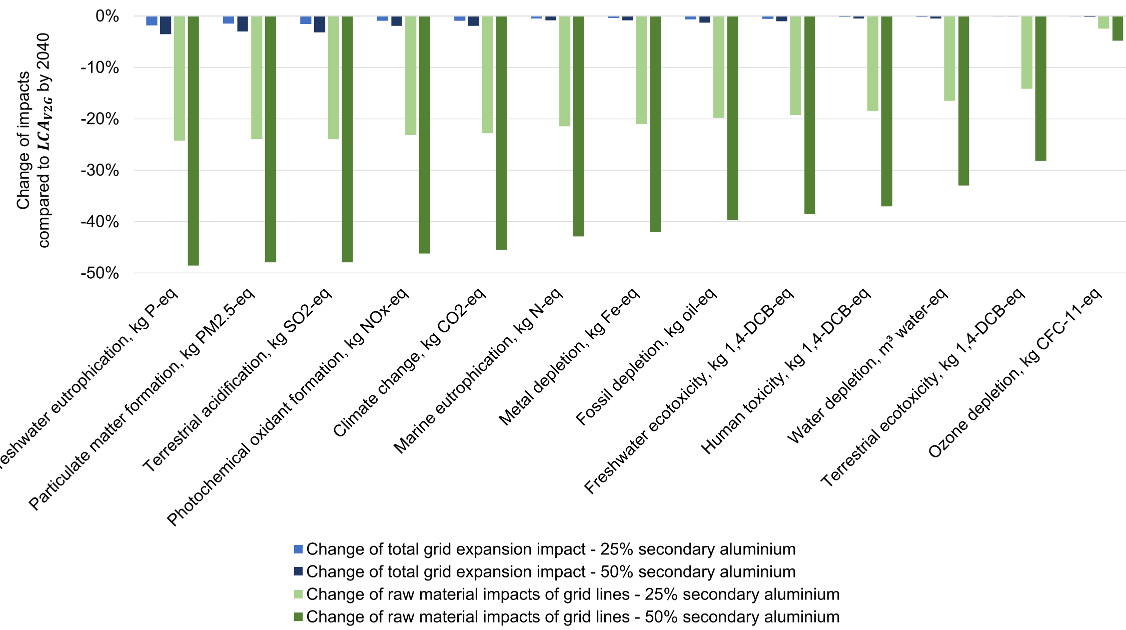

Fig. 5. Change of impacts of grid reinforcement total (LCA_{V2G}) and for the phase of raw materials in grid lines by 2040, sensitivity on the usage of secondary aluminum.

expansion ($\boldsymbol{LCA_{V2G}}$). In contrast to the sensitivity results of a changing EMF, however, the usage of secondary materials has little impact on the total results of systemic effects ($\boldsymbol{LCA_{V2G}}$), with less than -5 % across all impact categories. As outlined in Section 3.2, this is due to the comparatively highest impact share of power losses. We include the changes in raw materials' life-cycle phase to further conclude on the changing impact specifically attributable to grid lines. A higher share of secondary aluminum significantly lowers all impact categories except ozone depletion. These reductions vary between −49 % and -28 % in a scenario with 50 % secondary aluminum and between −24 % and -14 % in the case of 25 % secondary aluminum.

3.4. Comparison to the technology level

Changes between the scenarios 'V2G' and 'Mixed' not only concern systemic effects on the distribution grid but also those on the technology level. Regarding the operation phase of BEVs, Table 6 depicts the annual impacts resulting from (dis-)charging per scenario and the respective difference to the 'Baseline,' i.e., direct charging. Following the method after Fattler (2021), see Section 2.4, electricity discharging volumes enter the balance with a negative sign as the substitution of comparatively more GHG-intense electricity generation in hours of discharging is included in the system boundaries of operational emissions. In the case of 'V2G', reductions from discharging exceed the emissions from charging, and the impact thus reaches a negative sign with -81.1 $kgCO_2$-eq./BEV. Since BEVs apply a cost-optimized charging strategy, this is due to the inverse correlation between the electricity price and the share of RE in the electricity mix of the respective hour (see Appendix, Fig. A.3). In the 'Mixed' scenario, reductions from discharging do not exceed those of charging and operational impacts result into 82.1 $kgCO_2$-eq./BEV. Regarding the difference to the 'Baseline' scenario, which causes 130.6 $kgCO_2$-eq./BEV, both the 'V2G' and 'Mixed' scenarios lead to net impact reductions with -211.8 and -48.5 $kgCO_2$-eq./BEV (Table 6).

Table 6
BEV's annual impact of operation phase (GWP 100) in kg CO2-eq./BEV per scenario and difference to 'Baseline' by 2040.

Annual Climate Change (GWP 100) of operation phase of BEVs by 2040 in $kgCO_2$-eq./BEV	V2G	Mixed
Total	−81.2	82.0
Thereof charging	*169.0*	*100.5*
Thereof discharging	*−250.2*	*−18.4*
Total Δ to 'Baseline'	**−211.8**	**−48.5**

In contrast to the reductions in operational emissions, annual impacts determined for ICT infrastructure required for bidirectional charging strategies exceed those of direct charging. While both the 'V2G' and 'Mixed' charging strategies involve additional components, the operating hours in the 'V2G' scenario are higher, i.e., hours of (dis-) charging (see Appendix, Table A.2). Results show an impact of 9.9 kg CO_2-eq./BEV for ICT required for direct charging in the 'Baseline' scenario. In comparison, those of the 'V2G' and 'Mixed' scenarios reach 28.2 and 24.8 kg CO_2-eq./BEV, respectively (see Appendix, Fig. A.1). The impact of ICT infrastructure thus increases by 18.3 and 14.9 kg CO_2-eq./BEV compared to the 'Baseline' scenario respectively.

Adding up these differences, the reductions of operational emissions overcompensate the sum of impacts caused by determined systemic effects, i.e., repercussions on the distribution grid and the ICT of charging infrastructure. The 'V2G' and 'Mixed' scenarios thus lead to a net decrease of −95.8 and −30.2 $kgCO_2$-eq./BEV, respectively, by 2040. This suggests that while bidirectional charging strategies have some negative impacts on climate change, the overall effect is a reduction in emissions. (Fig. 6)

4. Discussion

In the following, we reflect on the core findings of the article's research questions. We contextualize our results in scientific literature and point out the limitations of this study.

1. *What are the prospective life-cycle environmental effects caused by repercussions within distribution grids resulting from a high penetration rate of bidirectional charging strategies?*

In line with existing simulations on the effects caused by a diffusion of V2G charging on the low-voltage grid (see Müller et al. [17], Englberger et al. [45]), our results show significant repercussions in the 'V2G' scenario. LCA results show an additional impact of 97.8 kg

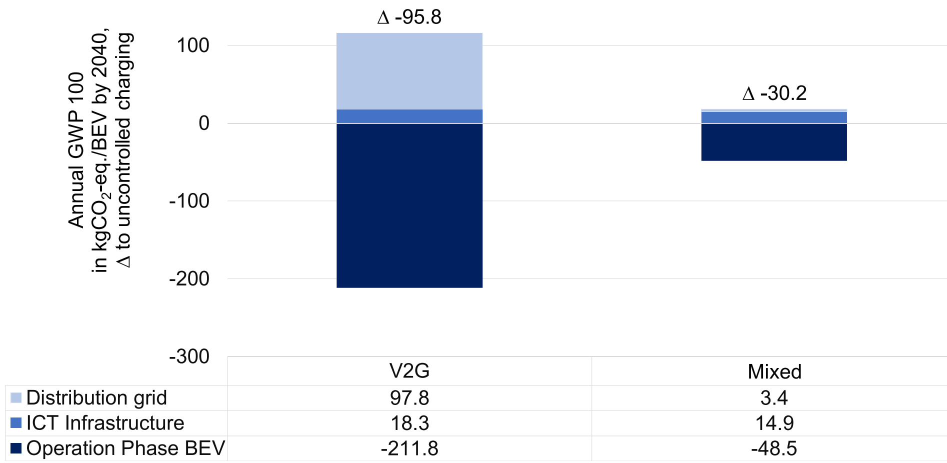

Fig. 6. Annual impacts (GWP 100) in kg CO_2-eq./BEV of effects on the system (power losses and expansion of distribution grid) and technology level (ICT infrastructure and operation phase of BEV) by 2040, Δ to direct charging.

CO_2-eq./a per BEV in the 'V2G' case compared to the 'Baseline' scenario by 2040. Although lower compared to the 'V2G' case, the impact of the 'Mixed' scenario still exceeds that of the 'Baseline' scenario by 3.4 kg CO_2-eq./a per BEV. The analysis identified the following reasons for the increased impact in cases of bidirectional charging and the differences between the 'V2G' and 'Mixed' strategies:

First, bidirectional charging involves higher electricity volumes charged and additionally discharged, which causes further power losses within the grid. This is especially true for losses in grid lines, which increase by 61 % in 'V2G' and 9 % in the 'Mixed' scenario compared to direct charging by 2040. The contribution analysis on LCA results shows that power losses and, thus, the operation phase of the grid contribute the most across all impact categories.

Secondly, the charging process follows the spot market price in the 'V2G' charging case. High charging simultaneities contribute to the increase of grid reinforcement requirements in the 'V2G' scenario. Raw materials used in grid components are responsible for most of the remaining impact shares. Therefore, aluminum used for grid line expansions is the main contributor. In total, 540 km of lines are necessary to meet the demands in the 'V2G' scenario in the modeling time frame (2020–2040) (cf. 142 km added in the 'Baseline' scenario). To put this figure into context: Using the simplified assumption of a linear expansion over the 20 years would correspond to an annual increase of 0.9 % of the initial grid length (3,016 km by 2020). The relative growth of the circuit length of Germany's low-voltage grid from 2022 to 2023 amounted to +0.6 % in total and +0.5 % for cables (84 % share of grid lines are cables, 16 % overhead lines) [26].

In contrast, the 'Mixed' scenario includes V2G, V2H, and direct charging. These diversified charging strategies reduce grid lines' expansion rates (−23 %) and transformer replacements (−6 %) in the investigated grid area. However, the impact caused by the above-mentioned increase of power losses compared to the 'Baseline' scenario exceeds the impact reductions due to lower grid reinforcement requirements. Consequently, there is still a net increase in environmental effects per BEV associated with 'Mixed' charging across all impact categories.

A sensitivity analysis of the national electricity mix indicates that the ongoing defossilization of electricity generation can significantly reduce the total impacts in several categories, first and foremost, fossil depletion and climate change. However, a higher share of RE shows slight increases in other impact categories, e.g., human toxicity and impacts related to water or metal depletion. These correlations were also identified by studies dealing with the impacts of future energy systems. For example, Naegler et al. [46] conclude that a decrease in GHG emissions in Germany's energy system comes along with the risk of increased human health indicators, land use, and consumption of mineral resources. Also, an investigation of reducing direct emissions in Switzerland by Vandepaer et al. [47] found increased impacts regarding metal depletion and human toxicity. The authors mention the upstream chain of RE-generation technologies, such as PV systems, as a primary contributor.

The results from the 'ambitious defossilization' scenario, which show reductions in GWP, also indicate slight increases in other impact categories due to the raw materials used in RE generation. This suggests that a comprehensive environmental assessment should consider multiple impact categories to provide a more balanced view of the trade-offs involved in large-scale V2G implementation. Future studies should aim to include a broader range of environmental impacts to better inform policymakers and stakeholders about the overall environmental implications of bidirectional charging.

Results of a sensitivity analysis on using secondary aluminum in grid lines show significant reductions in most impact categories within the life-cycle phase of raw materials. However, from the perspective of the total impact caused by repercussions within the grid, the reductions of secondary aluminum are relatively marginal as the operation phase (power losses) dominates the total impact. Nevertheless, there might be improvements in future production processes and upstream chains of grid components, as well as sorting technologies for the recycling of metals, such as those proposed for aluminum by Grimaud et al. [42].

2. *Compared to other environmental effects due to bidirectional charging, what is the magnitude of these systemic impacts on distribution grids?*

Among potential environmental effects, this article focuses on a comparison of determined systemic impacts to consequences caused on the technology level. Hereby, we focus on the implications of climate change (GWP) and include those caused by respective ICT infrastructure and the operation phase of BEVs. In line with the system boundaries of the first research question, the LCA investigates the differences between the 'V2G' and 'Mixed' scenarios compared to the 'Baseline,' respectively. In addition, the effects of the V2G scenario on the consequences of national electricity generation are discussed, which were examined in an earlier study.

Results indicate that V2G charging can achieve a balancing effect in the electricity market in a RE-based future energy system when following the spot market price. This is due to the correlation between the spot market price and the share of RE in electricity generation (see Appendix, Fig. A.3). In the event of RE shortages and high electricity prices, the function of BEVs as flexible storage and feed-in is utilized, thus serving as an economical flexibility option. In this study, we apply an average EMF of the grid mix to determine BEV's operational impacts related to discharging. The average EMF is a measure of the emissions intensity of the grid mix. Another approach is to use marginal EMF, which is the change in emissions intensity resulting from the last unit of electricity consumed or produced [48]. Discussing both approaches, Fattler [24] concludes that considering a marginal EMF significantly increases the GHG emission reduction potential of V2G. Accordingly, marginal EMFs do not represent an accurate assessment indicator due to high volatility and poor representation of RE. Taking on a third approach, other studies argue that V2G replaces traditional regulation services provided by gas turbines [49,50]. The avoided emissions are credited negatively to the BEV in case of discharging. However, this approach would likely result in overestimating the GHG reductions. We thus apply the average EMF in the respective hour of discharging resulting from the modeling, following the findings of Fattler [24].

Results on the technology level show that bidirectional charging leads to net reductions in operational emissions of BEVs. Compared to direct charging, emissions are decreased by 95.7 kg CO_2-eq./a per BEV in the 'V2G' case (vs. decrease by 30.2 kg CO_2-eq./a in the 'Mixed' case). Even when including the more significant impacts from ICT and systemic repercussions within the distribution grid, the comparatively high reductions in the GWP during the operation phase lead to an overall environmental benefit of bidirectional charging. Grid reinforcements are required for large-scale implementation of V2G charging (up to 100 % participation) to achieve such high reductions for all vehicles. However, this might not be technically or economically feasible. Recommendations include developments towards using diversified charging strategies, such as a combination of V2G and V2H, as shown by the results of the 'Mixed' scenario in this article.

Repercussions of bidirectional charging on the German power system were investigated in a previous study by Wohlschlager et al. [13]. In line with this article, the use case of V2G charging based on the spot market price, a large-scale diffusion of BEVs, and other governmental climate targets were investigated. Although the study applies different system boundaries for the pLCA, such as focusing on national electricity generation rather than rural distribution grids, the scenario assumptions of large-scale V2G charging applications are comparable to this article. Results indicate that additional storage capacities from BEVs in the 'V2G' scenario lead to increased integration of volatile RE, primarily from PV. Consequently, the total emissions caused by German power generation in 2030 decrease from 48.0 tCO_2-eq. in the reference case to 47.1 tCO_2-eq. in the 'V2G' scenario. The authors conclude that V2G charging is a valuable flexibility option, accelerating the medium-term transition to an electricity system based on RE. For long-term effects, the study indicates that using BEV batteries for the energy system might offer other environmental advantages, such as decreased raw material demands for stationary BESS [13].

Concluding from the comparison of these different effects on the system and technology levels, the adverse environmental impacts of V2G charging on local distribution grids can be overcompensated. This is due to the decreased emissions at the technology level (BEVs) and the potential increase of RE in the power system. However, this article's comparison focuses on the impact category of climate change. This limitation, along with other limitations, is further discussed in the next section.

4.1. Limitations

This study is conducted for a case of rural distribution grids in Southern Germany. The case study is only slightly representative since local conditions like building structure and weather conditions strongly influence the grid topologies and their loads. Furthermore, the 'V2G' and the 'Baseline' scenarios represent two extreme cases (100 % of one single charging strategy). This choice was made to investigate the maximum repercussions on distribution grids and how these compare to the potential benefits of GHG emissions during BEV operation in the evaluation per vehicle in Section 3.4.

On the other hand, the share of charging strategies assumed as a realistic case in the 'Mixed' scenario was determined in an interactive stakeholder process. The percentual combination of charging strategies in Germany by 2040 thus represents the industry's viewpoint. The reality might vary depending on external factors such as regulatory developments and technological advancements. In this article, no sensitivity analysis is applied to the percentual share of use cases in the 'Mixed' scenario. Müller [51] modeled additional scenarios using the tool 'GridSim.' In summary, a higher share of V2H prevents grid bottlenecks, but only in a very small percentage of networks. The V2H use case is thus of limited significance to the power grids despite being attractive to customers. In contrast, when flexibility options are optimized using the same logic, such as following a price signal in the case of V2G, due to increased simultaneous behavior, grid overloads increase significantly. An increase in V2G charging would thus influence the grid repercussions more considerably than an increase in V2H. Details on the impacts per use case can be found in the appendix of Müller [51]. Researchers can follow the presented method of combining distribution grid simulations and a pLCA to investigate other scenarios and grid areas.

For determining the annual values of grid expansion in 2040 as the reference year for the LCA, the method assumes a linear expansion rate between 2020 and 2040. The average annual expansion requirements serve as a reference point, acknowledging that determining annual network expansion needs is highly individual, influenced by local conditions, and varies between countries and distribution grid topologies. A detailed annual analysis of network expansion requirements would necessitate an in-depth analysis of the age structure of components, network expansion plans, and other factors that fall outside the scope of this study.

Regarding the techno-economic simulation, the underlying time series on the spot market price resulting from an energy system optimization is static. The optimization of the charging processes in the grid simulation has no effect on the electricity market, the merit order, or the price signal. Accordingly, there is also no feedback on the EMF of electricity between the scenarios. A slightly lower simultaneity of the BEV charging processes can be assumed. Especially in the case of V2G, the presented LCA results tend to be overestimated. The simultaneity in the simulation is further influenced by assuming that BEVs are always plugged in when they return from a trip and can participate in electricity trading. This is a simplification because modeling a vehicle's plug-in probability would complicate the linear optimization of the charging behavior, resulting in a mixed-integer linear problem. Also, charging simultaneities may likely cause increased repercussions in the medium-voltage level, which is outside the system boundaries.

Concerning the pLCA framework developed in this article, applying a modified pLCI database allows for consideration of future developments in the background system. Besides information collected from manufacturers in the foreground, a few assumptions for the LCA were derived from the literature. Since investigated grid components, i.e., low-voltage cables and transformers, represent well-established technologies, no future-oriented changes regarding the foreground system have been made. Next, the article's LCA-based comparison of different effects focuses on climate change impacts (GWP). The sensitivity analysis on the electricity mix (Section 3.3) reveals that increased use of RE technologies and their required materials negatively influences other categories, e.g., human toxicity, water depletion, or terrestrial ecotoxicity (see Fig. 4). Future research on the effects of novel use cases in SES should consider multiple impact categories to provide a balanced view of the environmental trade-offs. This is crucial for policymakers and stakeholders to understand the full environmental implications and possibilities for mitigation.

Lastly, this study focuses on the environmental assessment. Whether the utilization of BEVs as small-scale flexibilities and the associated increased need for grid expansion are economical solutions to achieve defossilized energy systems is out of scope. A techno-economical and environmental comparison to alternatives, e.g., stationary battery storage systems or large-scale flexibilities at higher voltage levels, is recommended. Additionally, the large-scale realization of bidirectional charging hinges on the digitalization of the energy system. This requires speed and workforce to implement digital infrastructure, such as smart meters, which has been progressing slowly in some countries, including Germany.

4.2. Contribution

Overall, this article contributes to understanding the impacts of bidirectional charging by bringing different perspectives – technology and system level – into relation. The contribution is two-fold. To enhance the perspective of systemic impacts, we first develop and outline a method to assess impacts resulting from repercussions caused within distribution grids. The method combines the approaches of techno-economic modeling and a pLCA and can be applied in further research to evaluate other geographical scopes or use cases. Secondly, applying the case study of a rural German distribution grid area provides empirical results on the impacts of a large-scale implementation of different bidirectional charging strategies by 2040. Simulation results provide insights for utilities and independent system operators on the long-term grid expansion requirements caused by large-scale BEV penetration and how different charging strategies influence these requirements. This article further demonstrates the magnitude of associated systemic environmental effects. This is shown by determining and comparing the consequences per charging strategy to the GWP on the technology level, using equal scenarios and thus a consistent pLCA approach. Results provide insights for industry and policy on the prospective impacts associated with bidirectional charging strategies depending on their implementation.

5. Conclusion & outlook

This article enhances environmental assessments of bidirectional charging by considering systemic impacts caused by repercussions within distribution grids. As a methodological contribution, the article provides the required steps to combine techno-economic modeling of distribution grids and to conduct a prospective Life Cycle Assessment with consistent integration of future developments. We prove the method's suitability by applying it to a case study with a regional focus on Southern Germany. Considering the penetration of battery electric vehicles in the grid simulation by 2040, a scenario with direct charging serves as the baseline. The assessment compares grid impacts to those resulting from scenarios with Vehicle-to-Grid charging and a mix of Vehicle-to-Grid, Vehicle-to-Home, and direct charging strategies. These systemic impacts per scenario are set in relation to the environmental effects at the technology level, i.e., battery electric vehicles operation and charging infrastructure. The discussion includes a reflection on possible systemic effects on power generation and storage.

In the case of a large-scale implementation of Vehicle-to-Grid charging following the spot market price, simulation results reveal considerable repercussions on power losses and expansion requirements of low-voltage distribution grids. Compared to direct charging, associated Life Cycle Assessment results indicate an additional impact of 97.8 kg CO_2-eq./a per battery electric vehicle. Significant increases in power losses, the primary contributor to impacts, highlight the need to reduce charging simultaneities. From a grid perspective, more balanced charging strategies are recommended. A scenario with a mix of Vehicle-to-Grid, Vehicle-to-Home, and direct charging within one grid area thus results in significantly fewer repercussions on distribution grids.

Regarding the environmental assessment, bidirectional charging causes higher impacts on the distribution grid level while achieving significant reductions in the operational emissions of battery electric vehicles. Adding up the consequences on different levels, scenarios with bidirectional charging show an overall decreased Global Warming Potential compared to direct charging. Especially in the case of Vehicle-to-Grid charging, the inverse correlation between the electricity price and the share of renewable energies in electricity generation leads to a considerable reduction in operational emissions of battery electric vehicles. These reductions exceed the impact of climate change caused by increased power losses and expansion requirements in low-voltage grids. In addition, reflecting on previous analyses that investigate the effects of bidirectional charging on the power system reveals its potential to accelerate the integration of renewable energies. While this article's comparison focuses on the impact category of climate change, future research should investigate effects in other life-cycle impact categories.

Recommendations for industry and policy include fostering balanced charging strategies that further consider local grid conditions to reduce repercussions on grid infrastructures. Other geographical scopes and grid topologies can be investigated for further research using the provided method. Also, we recommend examining the repercussions at higher voltage levels and comparing them to alternative flexibility options. To minimize impacts caused by novel use cases as part of the transformation towards decarbonized smart energy systems, further research and development should be encouraged to improve production processes and upstream chains that allow measures towards a circular economy. This can decrease the impacts of grid expansion components, as discussed in this study, as well as the impacts of renewable energy generation, vehicles, and required information and communication technology.

To conclude, this article's relevance is to provide a holistic picture of the intended and potentially unintended environmental consequences of use cases in smart energy systems. Compared to existing Life Cycle-based assessments of bidirectional charging, the originality lies in including systemic effects specifically caused by repercussions within distribution grids. This article enhances the methodological toolkit by providing a blueprint for a prospective Life Cycle Assessment of such. Investigating different variations of use cases and associated impacts can lead to more sustainable planning principles before large-scale implementation. The case study on bidirectional strategies of battery electric vehicles shows that strategic implementation of diversified use cases offers the potential for environmental benefits while providing flexibility to the energy system and economic benefits to end-users.

CRediT authorship contribution statement

Daniela Wohlschlager: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Janis Reinhard:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Iris Stierlen:** Investigation, Writing – original draft. **Anika Neitz-Regett:** Writing – review & editing, Supervision. **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.

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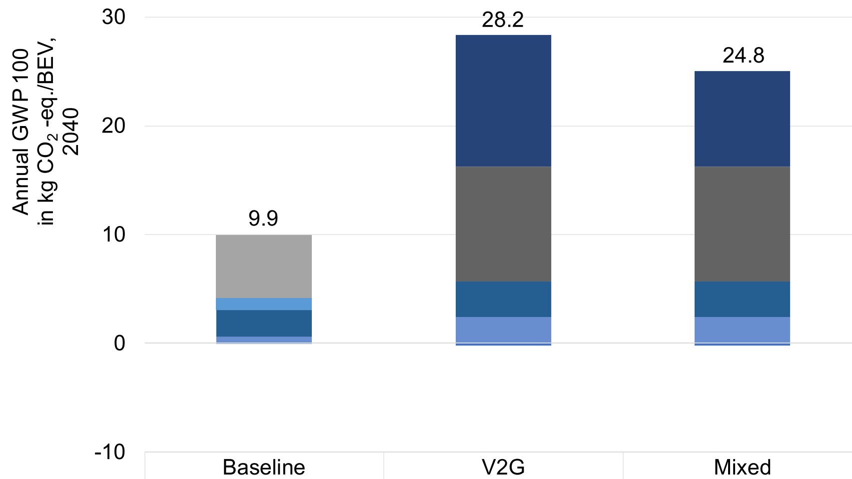
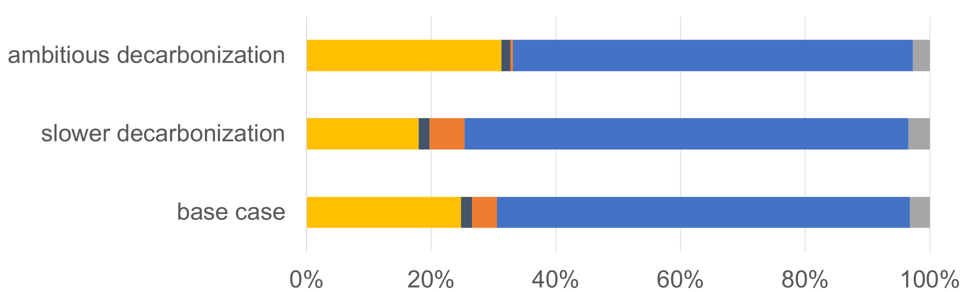
Appendix

See Fig. A1, A2, A3.



	Baseline	V2G	Mixed
End-of-life	-0.04	-0.2	-0.2
AC wallbox operation	5.8		
AC wallbox production	1.1		
DC wallbox operation		12.1	8.8
DC wallbox production		10.6	10.6
iMSys operation	2.5	3.3	3.3
iMSys production	0.6	2.4	2.4

Fig. A.1. Annual impact (GWP 100) for ICT infrastructure per charging strategy in kg CO2-eq./BEV by 2040, modified after Wohlschlager et al. (2022).



	base case	slower decarbonization	ambitious decarbonization
PV	25%	18%	31%
Hydro	2%	2%	1%
Natural gas	4%	6%	0%
Wind	66%	71%	64%
Others	3%	3%	3%

PV Hydro Natural gas Wind Others

Fig. A.2. Electricity mix for the sensitivity analysis on the annual average EMF.

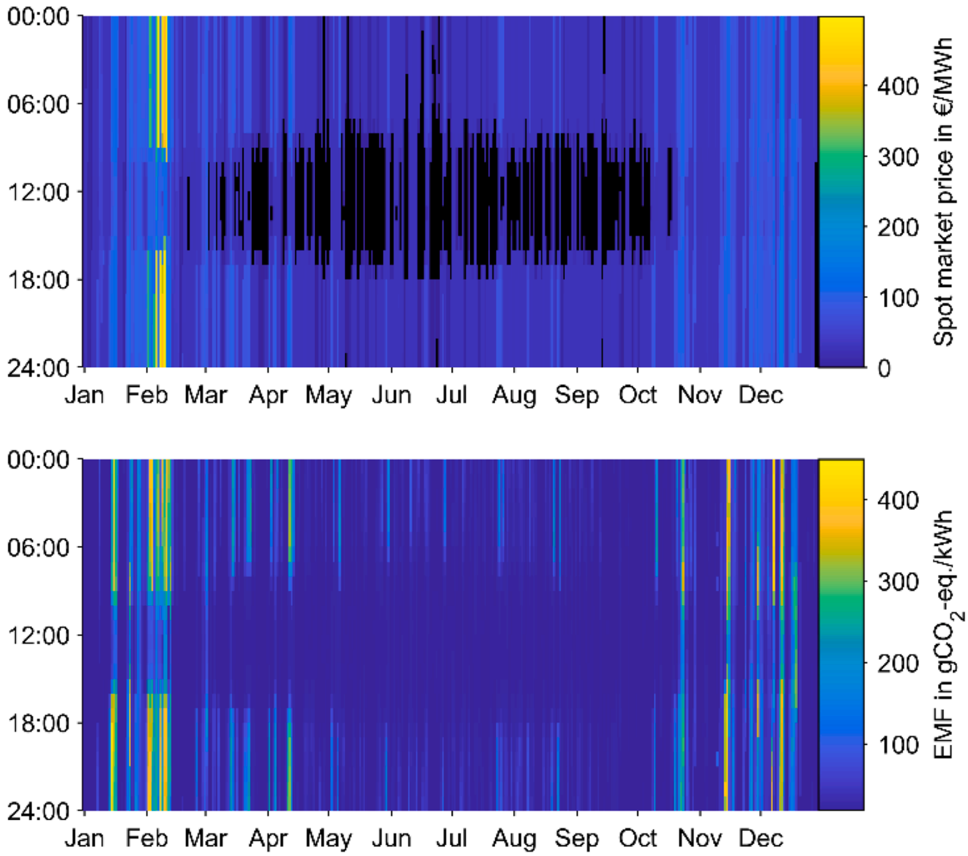


Fig. A.3. Correlation between the spot market price and average EMF of electricity generation resulting from the ESM per hour of the year in 2040.

Table A.1
Material composition of the grid line and the transformer as modeled in the LCA.

Material (Ecoinvent process)	Cable NAYY-J 4 × 240 SE **Weight [kg km^{-1}]** **(share of total weight [%])**	Transformer 630 kVA **Weight [kg/unit], (share of total weight [%])**
PVC (Polyvinylchloride, suspension polymerized)	2,016 (58)	–
Aluminum (Aluminum, primary, cast alloy slab from continuous casting)	2,784 (42)	–
Steel, high alloy (Steel, chromium steel 18/8)	–	788.1 (37)
Steel, low alloy (Steel, low-alloyed)	–	404.7 (19)
Copper (Copper, cathode)	–	553.8 (26)
Mineral oil (Lubricating oil)	–	340.8 (16)
Paper (Kraft paper)	–	7.1 (0.3[1])
Porcelain (Ceramic tile [2])	–	7.1 (0.3)
Wood (Sawnwood, softwood, raw)	–	7.1 (0.3)
Rubber (Synthetic rubber)	–	7.1 (0.3)
Acrylic varnish (Acrylic varnish, without water, in 87.5 % solution state)	–	7.1 (0.3)
Silicone products (Silicone product)	–	7.1 (0.3)
Total	**4,800**	**2,130**

[1] The manufacturer indicates the remaining materials of paper, porcelain, wood, rubber, acrylic varnish, and silicone products with < 1 % each; the shares are distributed equally among these materials.
2 No Ecoinvent product on porcelain available; due to marginal weight share, we use 'ceramic tile' as a proxy.

Table A.2
Operating time of ICT charging infrastructure (wallbox) per scenario by 2040.

	Baseline	Mixed	V2G
Annual operating hours of wallbox per BEV by 2040 (h/a)	263	1,248	2,554

Table A.3
LCA results per impact category and life-cycle phase for systemic effects within the distribution grid, 'V2G' scenario (compared to 'Baseline').

Impact Category	Unit	Raw materials	Manu-facturing	Transport	Installation	Power losses	Decon-struction	Disposal/ Recycling	Total
Climate Change	kg CO_2-eq	15,750,877	537,913	363,136	3,146,833	8,741,947	4,249	1,285,424	29,830,379
Fossil depletion	kg oil-eq	4,182,824	227,781	134,208	562,681	3,352,799	1,402	83,116	8,544,810
Freshwater ecotoxicity	kg 1,4-DCB-eq	9,180	247	260	1,109	4,338	2	848	15,984
Freshwater eutrophication	kg P-eq	1,072	62	3	48	271	0	5	1461
Human toxicity	kg 1,4-DCB-eq	7,221,830	293,580	86,825	262,450	2,015,883	98	58,765	9,939,431
Metal depletion	kg Fe-eq	4,271,637	124,722	7,650	84,071	1,277,239	166	6,769	5,772,253
Marine eutrophication	kg N-eq	2,200	63	77	404	1,423	2	70	4,240
Ozone depletion	kg CFC-11-eq	1	0	0	0	1	0	0	2
Particulate Matter Formation	kg PM2.5-eq	53,554	1,173	834	4,416	14,590	17	1,769	76,354
Photochemical oxidant formation	kg NOx-eq	69,571	1,585	2,328	10,786	25,889	57	1,875	112,092
Terrestrial acidification	kg SO_2-eq	130,150	3,481	1,564	9,135	31,489	33	1,251	177,102
Terrestrial ecotoxicity	kg 1,4-DCB-eq	1,783	61	181	309	4,204	0	80	6,618
Water depletion	m^3 water-eq	80,571	7,178	609	15,610	89,389	5	1,699	195,061

Table A.4
LCA results per impact category and life-cycle phase for systemic effects within the distribution grid, 'Mixed' scenario (compared to 'Baseline').

Impact Category	Unit	Raw materials	Manu-facturing	Transport	Installation	Power losses	Decon-struction	Disposal/ Recycling	Total
Climate Change	kg CO_2-eq	−91,589	−303	−1234	−12,595	446,412	−16	−7,453	333,222
Fossil depletion	kg oil-eq	−23,516	−345	−447	−2,091	155,865	−5	−402	129,059
Freshwater ecotoxicity	kg 1,4-DCB-eq	−68	0	−3	−6	245	0	−9	159
Freshwater eutrophication	kg P-eq	−7	0	0	0	13	0	0	6
Human toxicity	kg 1,4-DCB-eq	−76,415	−128	−446	−3,151	162,382	−1	−813	81,428
Metal depletion	kg Fe-eq	−40,054	−76	−43	−623	87,331	−1	−83	46,451
Marine eutrophication	kg N-eq	−18	0	−3	−2	118	0	0	93
Ozone depletion	kg CFC-11-eq	0	0	0	0	0	0	0	0
Particulate Matter Formation	kg PM2.5-eq	−355	−1	−2	−19	749	0	−9	363
Photochemical oxidant formation	kg NOx-eq	−410	−2	−5	−40	1,576	0	−8	1,111
Terrestrial acidification	kg SO_2-eq	−955	−2	−5	−36	1,772	0	−6	768
Terrestrial ecotoxicity	kg 1,4-DCB-eq	−36	−1	−12	−13	434	0	−2	370
Water depletion	m^3 water-eq	−570	−15	−39	−84	6,131	−1	−19	5,403

Data availability

Data on the Life Cycle Inventory of modeled components is found in the Appendix of the article.

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