Assessing Environmental Effects of ICT in Smart Energy Systems - Case of Bidirectional Charging

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Abstract

Current research highlights the benefits of digitalization that enables smart energy systems (SES) based on renewable energy sources. These studies often omit unintended environmental side effects. Next to an additional resource and energy use of information and communication technology (ICT) as effects of 'first-order', impacts of 'higher-order' are caused by changes in user behavior as well as repercussions in the overall energy system. This work develops a framework for a holistic environmental assessment of use cases in SES. To allow this evaluation, the work combines the methods of prospective Life Cycle Assessment (pLCA), and energy system modeling. The feasibility is shown by applying the resulting framework to the use case of bidirectional charging of battery electric vehicles (BEVs). The initial results indicate that effects of higher-order pose a relevant environmental impact attributable to smart charging strategies that have not been sufficiently investigated in previous studies.

Keywords

Life Cycle Assessment, Higher-Order Effects, Battery Electric Vehicles, Vehicle-to-Grid,

1. Motivation and background

The ambition towards climate neutrality implies fundamental changes in centralized and highly fossil-based energy systems. Combined with the rising share of volatile power generation from decentralized renewable energy sources (RES), the ongoing electrification of consumers and resulting changing consumption patterns increase the complexity within historically grown energy infrastructures. The use of information and communication technologies (ICT) is regarded as the facilitator towards a transformation into smart energy systems (SES) (see [1]) based on RES [2].

Besides new use cases for grid operators and energy suppliers, ICT enables additional applications for end consumers such as private households [3]. This includes smart charging strategies that have been on the rise to enable an efficient integration of battery electric vehicles (BEVs) into the energy system. Next to unidirectional charging, bidirectional charging management (BCM) of BEVs allows to discharge electricity back into the grid

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In: B. Combemale, G. Mussbacher, S. Betz, A. Friday, I. Hadar, J. Sallou, I. Groher, H. Muccini, O. Le Meur, C. Herglotz, E. Eriksson, B. Penzenstadler, AK. Peters, C. C. Venters. Joint Proceedings of ICT4S 2023 Doctoral Symposium, Demonstrations & Posters Track and Workshops. Co-located with ICT4S 2023. Rennes, France, June 05-09, 2023.

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and thus the usage of BEVs as flexible storage units. Depending on the purpose of the use case, there are different charging strategies as outlined by Kern et al. [4]. Vehicle-to-grid concepts (V2G) thus include cost-optimized BCM aiming at minimized operational costs for the end user, i.e., charging in times of low electricity prices. Another use case is the provision of grid stability [4]. Applications specifically on a household level, i.e., vehicle-to-home (V2H) charging, include the self-consumption of local RE generation, typically from PV [5].

With regards to the environmental sustainability of bidirectional charging, the intended environmental effects of charging in times of low electricity prices and thus high RE availability include lower operational emissions of BEVs. A wide range of literature on smart charging concepts focused on operational emissions as shown in a review by Tang et al. [6]. Existing methodological frameworks on the environmental assessment of ICT in general (see review by Pohl et al. [7]), however, distinguish between effects of *'first-order'* (direct) and effects of *'higher-order'* (indirect). Effects of first-order comprise the footprint of ICT components, typically determined by a Life Cycle Assessment (LCA). Effects of higher-order encompass both intended benefits as well as negative side effects beyond the technology perspective. These include repercussions caused on the user level that increase or decrease the environmental impact [8]. Regarding the user level, research on bidirectional charging indicates that driving and charging behavior highly impacts the flexibility potential of BEVs and thus the environmental performance [9], [10]. An evaluation on emission-optimized bidirectional charging shows that intended environmental effects such as the reduction of operational emissions of BEVs depend on the accepted state-of-charge (SOC) at departure or SOC-dependent plug-in behavior [11]. The relevance of considering effects on the user level when determining the environmental impact of ICT-enabled concepts is also highlighted for other applications in SES, such as in a study on emission-saving potentials of smart home systems [12]. Lastly, higher-order effects include those on the system level. Previous investigations on energy system-wide effects of bidirectional charging include impacts on the technology landscape of electricity generation and storage (see [13]). In addition, a study by Müller et al. [14] showed that bidirectional charging based on price signals leads to higher simultaneity and thus increased grid reinforcement requirements. Such an expansion involves a certain environmental impact not yet considered in previous investigations that rather focused on techno-economic aspects. In this work, investigated systemic effects thus include repercussions on generation and supply as well as on energy transmission and distribution infrastructures (e.g., electricity grids).

Overall, literature shows that a holistic environmental evaluation of use cases in SES requires the assessment of various effects on different levels. As outlined above, previous environmental evaluations of smart charging strategies primarily focused on quantifying single effects, either of first- or higher-order. Until now, holistic efforts to outline, quantify and compare the impacts caused on these levels are missing.

To contribute to the identified research gap, this doctoral thesis addresses the following research questions (RQ):

1. What is a holistic framework to assess the lifecycle-based environmental impacts of digital use cases in SES?
2. Applied on the example of bidirectional charging of BEVs, which parameters have the greatest influence on the environmental performance?
3. What are appropriate recommendations on the technical design and the implementation of bidirectional charging strategies from a systemic perspective?

The overarching purpose of this thesis is to provide a guideline for a holistic environmental assessment of ICT-enabled use cases in SES. To test the feasibility of the framework, it is applied to assess bidirectional charging of BEVs. Next to deriving recommendations for a sustainable technical design of ICT, results shed a light on impacts caused on the user and system level and how these can be minimized.

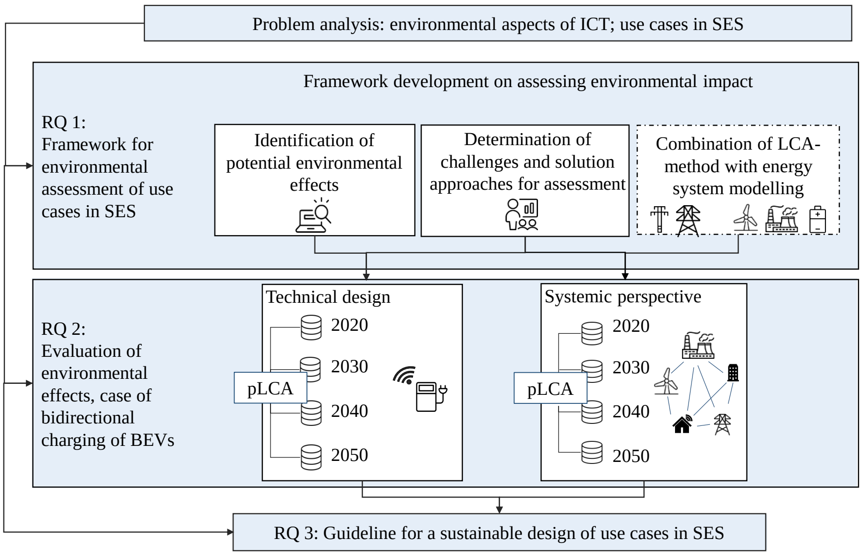
2. Research approach

Fig. 1 illustrates the research design. With respect to the growing relevance of the upstream chain within a decarbonized energy system (e.g., production of power generation technologies), the determination of both first- and higher-order effects follows the approach of an LCA. More specifically, a prospective LCA (pLCA) is applied to consider future policy scenarios and associated technological consequences in future years (e.g., changing efficiencies or resource use along the upstream chain). To develop a framework for the subsequent assessment, RQ 1 involves the following steps:

- Identification of potential environmental effects
- Determination of challenges and solution approaches for assessment
- Combination of LCA-method with energy system modelling

To answer RQ 2, the developed framework is applied on the example of bidirectional charging of BEVs, focusing on V2G charging as a use case. To determine recommendations on the technical design of ICT (first-order effects), a pLCA is conducted on required charging infrastructure and processes. Data for the Life Cycle Inventory (LCI) is derived from secondary data (publicly available technical data, literature) as well as empirically collected primary data (interviews with manufacturers and service providers, measurements on ICT data transmission within a field trail). To evaluate effects from a systemic perspective (higher-order effects), this work builds upon methodological considerations of combining energy system models (ESM) with LCA. In addition to results from techno-economic energy system modelling, results of grid simulations provide information on changes in grid reinforcement requirements (e.g., cables and transformers) when introducing V2G charging. Both results from V2G-scenarios modelled with techno-economic ESM as well as grid simulations serve as an input for a pLCA.

Next, the operational emissions of BEVs are modelled depending on the charging strategy. To integrate behavioral effects, i.e., caused on the user level, surveys and data measurements on behavioural parameters of the model (e.g., time and duration of charging, accepted SOC) are conducted within a large-scale field trial. Lastly, results from RQ 1 and RQ 2 serve to derive a guideline on how to assess environmental effects on different levels and recommendations for a sustainable technical design of emerging SES use cases.



BEVs… Battery electric vehicles; LCI… Life Cycle Inventory; pLCA… Prospective Life Cycle Assessment; SES…. Smart energy system ⬚ Input from existing models

Figure 1: Research design

3. First results

3.1. Effects of first-order

As part of this doctoral thesis, a pLCA was conducted to determine the first-order effects of required ICT to enable the use case of emission-optimized V2G charging. Details on methods and results are published in Wohlschlager et al. [15]. The investigation compares the footprint of required infrastructure and data processing for uni-, bidirectional and conventional charging for the years 2020 and 2040 respectively. The analyzed use case is emission-optimized charging (uni- and bidirectional) of a private BEV over one year, assuming the driving profile of an average German household. Fig. 2 shows the required ICT as modeled for the analyzed use case. The system boundaries thus include smart metering infrastructure (smart meter gateway, modern metering devices) as well as a private wallbox operating with alternating current (AC) in the case of unidirectional and uncontrolled charging, and direct current (DC) in the case of bidirectional charging. Next to hardware, the analysis includes data processing, i.e., data transmission and storage. By adjusting the emission factor of the charging current and taking into account future developments in LCI for the upstream chain based on a pLCA-approach, the global warming potential (GWP) is determined. The pLCA shows a significantly lower impact of the infrastructure for conventional charging compared to bidirectional charging by 2020 (57.5 kg CO_2e/a for uncontrolled charging, 145.4 kg CO_2e/a for bidirectional charging). [15]

Due to the electricity consumption in the operational phase, the wallboxes contribute the most in all cases, while data processing is negligible. Assuming progressive decarbonization of the energy system and the associated reduction of the emission factor of electricity, first-

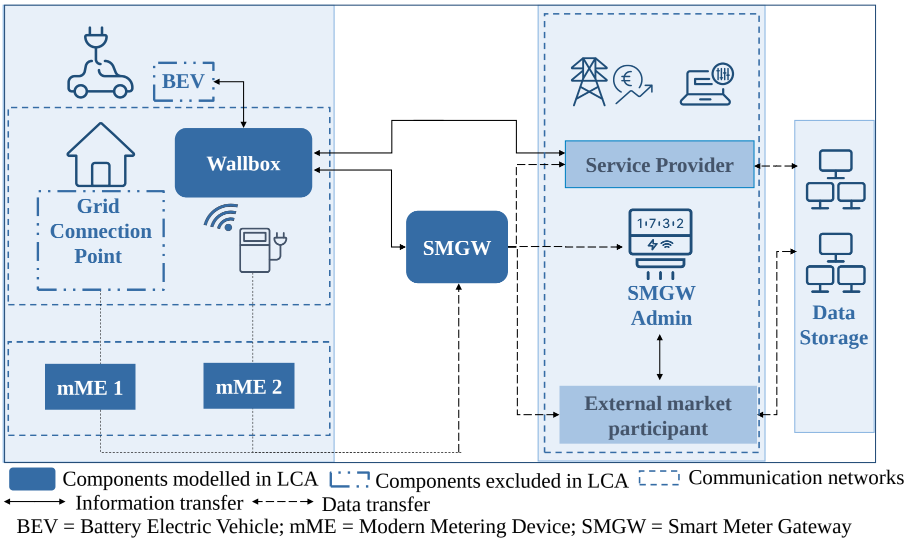


Figure 2: Required ICT infrastructure for bidirectional charging of BEVs, modified after [15]

order effects of charging infrastructure can be reduced by up to 56% for bidirectional charging until 2040. Conducted sensitivity analyses show that the highest potential to reduce first-order effects in the long term is to decrease the impact within the production phase of ICT hardware. Manufacturers should thus focus on sustainable manufacturing and the longevity of components.

To classify the quantified first-order effects, the LCA results are compared with the achievable reduction in operational emissions of electric vehicles through V2G charging, using a emission-optimized charging strategy as quantified by Fattler [11]. A direct comparison shows an overall environmental benefit of emission-optimized V2G charging. The reduction potential in operational emissions from BEVs thus exceeds the quantified first-order effects of charging infrastructure.

3.2. Effects of higher-order

Up to now, the analysis of higher-order effects focuses on an ex-post environmental assessment to combine the methods of ESM and LCA. The method builds upon previous investigations on assessing the systemic environmental impact of certain charging strategies (see [13]). The evaluation determines the life cycle-based emission factor (EMF) of the German electricity generation from 2020 to 2050, caused by an integration of bidirectionally chargeable BEVs (cost-optimized V2G) compared to a reference scenario. While in the first scenario, BEVs are considered as a flexible storage option with the possibility to fed electricity back into the grid, the reference scenario excludes the option of smart charging. By applying a pLCA, the work considers techno-economic developments within the background system by modifying the ecoinvent database. Hourly time series of power generation from an energy system model are combined with the determined LCA-based EMF per generation technology.

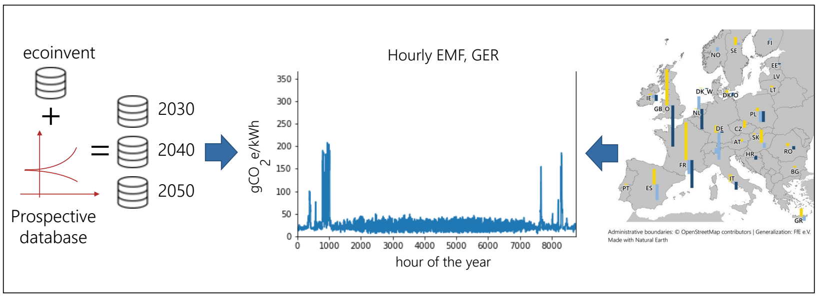


Figure 3: Methodological approach to determine hourly emission factors (EMF) of electricity

Fig. 3 illustrates the methodological approach as applied to calculate the hourly EMF for the use case of V2G charging in Germany (GER).

4. Conclusion and outlook

This work focuses on developing a framework to determine environmental effects of ICT-based use cases in SES with a subsequent application on the example of bidirectional charging of BEVs. The scientific contribution to the body of research on ICT sustainability assessment is two-fold: First, the developed framework serves as a blueprint for a holistic environmental evaluation of further use cases being developed in the context of SES. It provides an overview of approaches to assess environmental effects of first- and higher-order, with a focus on assessing systemic consequences by combining LCA with energy system modelling. Secondly, quantified results from the application on the use case of V2G charging provide an indicator for the most relevant levers regarding both the technical design of ICT, but also a sustainable integration of BEVs through smart charging from an energy system-wide perspective.

To date, effects of first-order were quantified through an LCA of ICT required for smart charging infrastructure. Also, a methodological approach was developed to address changes within the electricity generation as a systemic effect of higher-order. Next steps involve the application of the developed approach to quantify hourly EMF of national electricity generation considering scenarios with a diffusion of bidirectionally chargeable BEVs. Morevoer, simulations of the electricity distribution grid by Müller et al. [14] show a significant increase in peak loads and full-load cycles of BEVs when assuming emission- or cost-optimized V2G charging, which places an additional burden on power grids and operating resources. To investigate the related environmental impacts, the development and application of a method to assess systemic effects on electricity distribution grids is thus part of the next steps in this thesis. To evaluate effects on the user level, a user survey is prepared that will be applied in a large-scale field trial on testing use cases of BCM as part of the research project *unIT-e²*. Determined first- and higher-order effects are combined for a comparative evaluation of environmental effects associated with BCM of BEVs. Lastly, results will be combined to provide an overall guideline for a sustainable design of use cases in SES.

Acknowledgments

This contribution was conducted as part of the research project *unIT-e²* (funding code: 01MV21UN11), funded by the German Federal Ministry for Economic Affairs and Climate Protection.

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