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

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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).

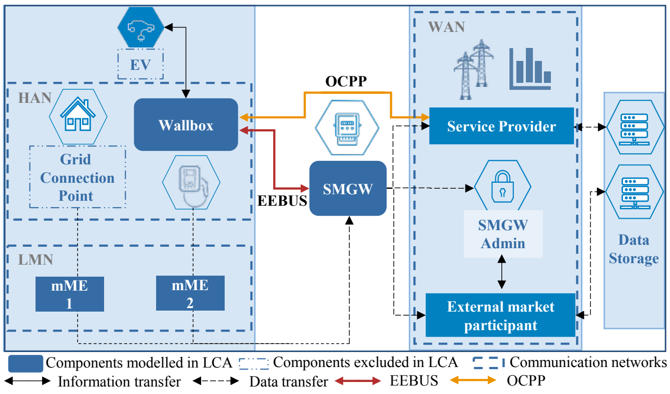
2. Method and LCI data

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.



EV = Electric Vehicle, mME = Modern Metering Device, SMGW = Smart Meter Gateway,
HAN = Home Area Network, WAN = Wide Area Network, LMN = Local Metrological Network

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.

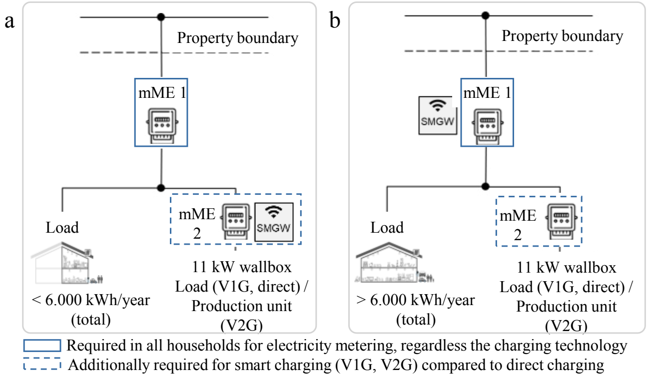


Figure 2: Infrastructure for charging in the scenarios (a) 'MIN'; (b) 'MID'

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].

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

Parameter	mME	SMGW	Wallbox	
			AC	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)
$t_{(dis\text{-})charging}^{1,2}$ (*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

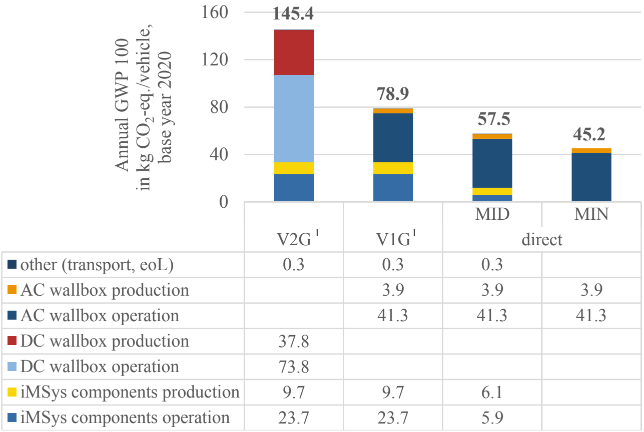
[1] includes regular daily operation, the standby mode of the SMGW and data transmission of the tariff application case (TAF 7) for metering data recording every 15 minutes, with transmission once per day

[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]	MID direct	MIN direct
■ 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

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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)

	mME	SMGW	Wallbox	
Component parameters			AC	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

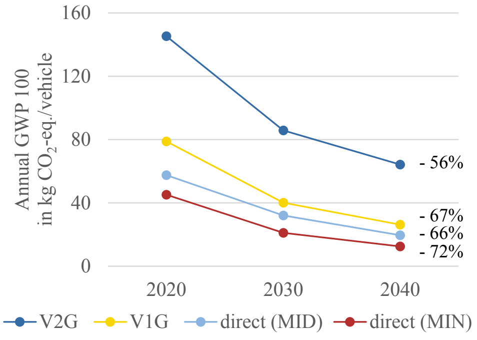

Fig. 4. Sensitivity of LCA results (GWP 100) of charging infrastructure in kg CO_2-eq. per vehicle and year with decreasing EMF of electricity, all scenarios

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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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.