Electricity Storage in Smart Energy Systems: Can Bidirectional Charging Make an Environmental Impact?

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Abstract:

Bidirectional charging is a smart charging strategy enabling the controlled charging and discharging of battery electric vehicles (BEVs). In a vehicle-to-grid (V2G) application of bidirectional charging, BEVs can send the stored electricity back into the grid, thus, serving as mobile storage systems. A large-scale implementation of this application could support the provision of flexibility in the smart energy system of tomorrow by substituting other electricity storage options such as stationary battery energy storage systems (BESS). This study evaluates the long-term environmental effects of a widespread deployment of bidirectional charging in the European energy supply sector using a prospective life cycle assessment (pLCA) approach. Therefore, two net-zero energy system model scenarios are compared, which have identical underlying assumptions, except for the capability of using the available BEV fleet for flexibility purposes. Variations in energy plant construction and operation are analyzed concerning global warming potential (GWP) and metal depletion (MD). Additionally, a sensitivity analysis has been conducted to assess the influence of considering BEV battery aging impacts accountable to V2G. Over the investigated time frame, from 2025 to 2050, it has been found that bidirectional charging could reduce greenhouse gas (GHG) emissions by 54.5 Mt CO_2-eq and metal resource utilization by 282.3 Mt Fe-eq. These reductions can be mainly traced back to the avoidance of the installation of stationary BESS. While this provides a noticeable advantage in metal resource preservation, decreases in GWP remain marginal compared to current levels. Results even show a rise in GHG emissions in the medium term, until 2042, as more renewable energy plants are constructed in this time frame. Indeed, the higher flexibility potential provided by BEVs, as compared to stationary BESS, has been found to accelerate the integration of renewable energies. The pLCA has been implemented in an automated Python-based framework, enabling the investigation of the environmental repercussions on the energy system of different technologies or policies, and is applicable to other scenarios in future research.

Keywords: life cycle assessment, smart charging, vehicle-to-grid, battery storage, battery electric vehicle, energy system scenarios

1 Introduction

A clean energy transition is at the core of the European Green Deal (European Commission, 2019) with the ambition of reaching net-zero greenhouse gas (GHG) emissions by 2050. The

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revised Renewable Energy Directive (RED III) (European Parliament, 2023) establishes the key role of renewable energies (RE) in reaching climate neutrality on that year, setting an accelerated RE consumption target of 42.5 % by 2030 on European Union (EU) scale. As a means of guaranteeing a successful integration of RE, load flexibilization and short-term electricity storage will be indispensable for counteracting the fluctuating availability of RE sources, especially wind and photovoltaics (PV). The growing load of battery electric vehicles (BEVs), in particular, needs to be controlled through smart charging strategies. As an extension of unidirectional smart charging (V1G), bidirectional charging enables electricity flows in both directions. In a vehicle-to-grid (V2G) application, bidirectional charging allows the dual use of BEV batteries in smart energy systems: on the one side to store energy for vehicle propulsion and on the other side to provide short-term storage capacity in the energy system by discharging electricity back into the distribution grid.

Implementing V2G on a large scale inherently affects the energy system and its environmental impacts. Xu et al. (2020) couple an energy system model (ESM)'s future electricity mix output with a prospective life cycle assessment (pLCA) approach to estimate the effect of different BEV charging policies on GHG emissions. They find that, in 2050, V2G could reduce the global warming potential (GWP) for electricity generation by 17 % compared to a system without controlled charging and by 11 % compared to one with V1G only. Yet, they do not consider alternative technologies for electricity storage in scenarios without bidirectional charging integration, which is unlikely given the expected expansion of RE (Wali et al., 2021; Weitemeyer et al., 2015).

Indeed, the broad deployment of V2G could replace stationary battery energy storage systems (BESS) in the future. BESS can be produced using newly manufactured battery packs (1st life BESS) or repurposed BEV batteries extracted at an early stage of their life span, thus extending their lifetime (2nd life BESS). The remanufacturing of battery packs having a much lower GWP than their initial manufacturing (Ahmadi et al., 2017; Philippot et al., 2022), 2nd life BESS could represent another means of decarbonizing the energy system alongside V2G. Zhao and Baker (2022) assess the life cycle impacts of future electricity supply opposing different options for electricity storage. They find that V2G implementation even increases the GWP of the electricity mix compared to stationary BESS. The increase is accentuated in the case of 2nd life BESS being preferred to 1st life BESS. However, their study does not account for endogenous energy system modelling, nor does it consider future-oriented modifications of specific environmental impacts.

Tackling this issue, Wohlschlager et al. (2024) compare prospective hourly emission factors of electricity in an ESM scenario with large-scale bidirectional charging implementation to a reference scenario using stationary 1st and 2nd life BESS only. They find that V2G has an insignificant effect on GHG emissions from electricity generation by 2045 but favors the medium-term integration of RE, thus temporarily accelerating the decarbonization of the electricity supply sector. However, they do not assess systemic repercussions of V2G on energy generation and storage capacity expansion and operation and their impact on other environmental indicators, such as raw metal utilization.

Indeed, battery packs require a vast amount of raw metals for their production process (McManus, 2012), among which most are featured on the European Commission's list of critical raw materials (European Commission, 2023). Moreau et al. (2019) showed that proven metal reserves are insufficient for meeting the worldwide metal requirements of a RE transition using newly manufactured batteries for electricity storage. Hence, it is relevant to study the impacts of different electricity storage technologies on metal depletion (MD) in addition to GWP.

This study aims to provide a more comprehensive view of the long-term ecological repercussions of utilizing BEVs as flexible storage options in the European energy supply sector. Considering multiple options for short-term electricity storage and evaluating the energy system as a whole, going beyond electricity production, the environmental cost of bidirectional charging is evaluated using a pLCA approach. Thereby, the following research question is to be tackled: “**How does the large-scale integration of flexibility potential from BEVs in smart energy systems through bidirectional charging affect the environmental impacts of the energy system?**”. Results provide insights on the GWP and MD resulting from changes in installed energy generation and storage capacities and primary energy consumption, compared to a system without V1G and V2G charging, from 2025 to 2050.

This study is structured as follows. In Section 2, a methodology for the environmental assessment of bidirectional charging impacts on the energy system is outlined. Section 3 provides insights into the results of the pLCA, which are then discussed in Section 4. The study closes with a short conclusion and outlook in Section 5.

2 Methodology

In this work, a pLCA is conducted in accordance with ISO 14040:2006 and ISO 14044:2006 and the definition given by Arvidsson et al. (2018). An automated Python-based framework has been developed to implement the pLCA. Replacing manual and time-intense investigations, the resulting framework allows an automated evaluation of how different technologies or policies impact the environmental effects of the energy system. This study

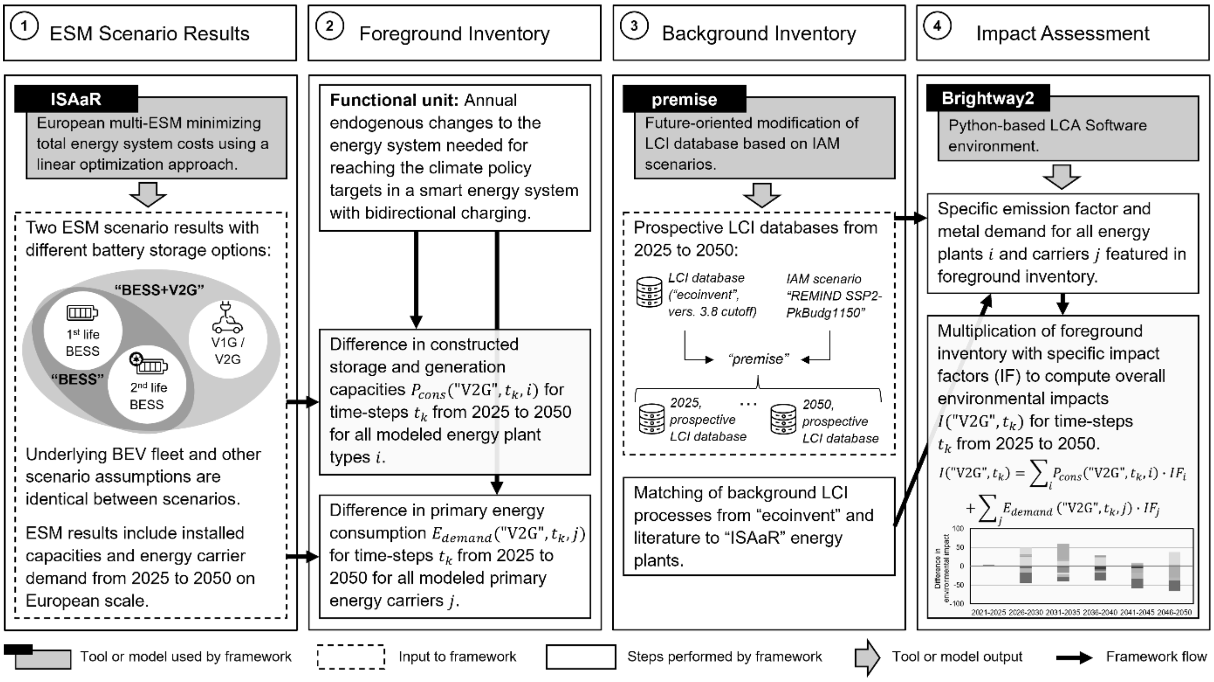

Figure 1: Overview on the methodology of the automated framework applied for evaluating prospective life cycle impacts of bidirectional charging.

portrays the results of applying the framework to bidirectional charging but could be applied to investigate other scenarios and measures in further research.

Figure 1 illustrates the methodology used to implement the automated framework. The framework performs an ex-post assessment taking static results from two ESM scenarios to set up the foreground inventory. To capture the variations in energy plant expansion and operation needed for decarbonizing the future energy system, a differential life cycle inventory (LCI) is created. This involves comparing two climate policy scenarios with equal underlying assumptions, except for the capability of the available BEV fleet to perform V1G or V2G. The scenarios are modeled using “ISAaR,” a linear optimization multi-ESM described in Kigle et al. (2022) that minimizes the energy system’s total costs. To comprehensively cover changes to the energy system, the difference in constructed storage and generation capacities and primary energy consumption is calculated for all modeled time-steps.

Prospective LCI databases for each future time-step evaluated by “ISAaR” are generated based on the “ecoinvent” LCI database and systematically modified with the “premise” tool to include social, technological and economic developments. They are, then, used to compute the specific GWP and MD per constructed energy plant capacity and consumed primary energy for all technologies featured in the foreground inventory. This makes up the background inventory of the pLCA and requires matching the ESM technologies with background processes of the prospective LCI databases. By coupling the results of the foreground and background inventory analysis, overall future environmental impact variations of bidirectional BEV integration can be assessed.

2.1 Goal and Scope Definition

The **goal** of the pLCA is to evaluate the long-term environmental consequences on the European supply sector of utilizing BEVs as flexible storage options. For this purpose, the **system** under consideration is defined as the changes in energy plant expansion and operation required to cover the European energy demand from 2025 to 2050. Those changes are defined using two net-zero scenarios, which only differ in the possibility of controlling the available BEV fleet for providing flexibility to the energy system, especially in the form of electricity storage. The **functional unit** derived from the definition of the system is the annual endogenous variations to the energy system needed for reaching the climate policy targets in a smart energy system with bidirectional charging.

Based on the adopted differential perspective, only comparison-based findings between both scenarios can be made and it is not possible to draw general conclusions on absolute impacts. Moreover, any non-environmental advantages or drawbacks of implementing V1G and V2G are not considered within the assessment but play a crucial role in decision-making, nonetheless.

Two **impact categories** are investigated within the scope of the pLCA: climate change and metal depletion. The applied impact assessment methods are “IPCC 2013 no LT, climate change, GWP 100a” and “ReCiPe Midpoint (H) V1.13 no LT, metal depletion, MDP”, respectively. The GWP is measured in tons of CO_2 equivalent (t CO_2-eq) and MD in tons of iron equivalent (t Fe-eq).

2.1.1 Energy System Model Scenarios

To comply with the goal of the pLCA, two ESM scenarios – “BESS” and “BESS+V2G” – whose only difference lies in the ability of the ESM to include bidirectional charging in the optimization lay the basis of the assessment. The ESM scenarios are modeled using “ISAaR”, which relies upon hourly final energy consumption (FEC) sector loads and RE site potential inputs for computing a cost-optimal future energy system. The “ISAaR” model covers the generation, conversion and storage of six energy carriers: electricity, heat, hydrogen, biomass, methane and liquid hydrocarbons. Böing and Regett (2019) outline the implemented linear optimization method.

The basis for the “BESS” and “BESS+V2G” scenarios is the updated version of the “solidEU” scenario. As described by Kigle et al. (2022), “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. 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 (ENTSO-E and ENTSOG, 2022). In both scenarios, an endogenous expansion of RE is only possible from 2035 onwards, before that, expansion targets are specified to the model.

The scenarios “BESS” and “BESS+V2G” used for this analysis include the novel possibility of modeling endogenous expansion of stationary BESS. Hereby, the options include both 1st and 2nd life BESS. The ESM limits the availability of 2nd life BESS 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 storage:

- In the “BESS” scenario, BEVs charge directly (uncontrolled) according to synthetic driving profiles by Fattler (2021) based on Nobis and Kuhnimhof (2018).
- In the “BESS+V2G” scenario, the ESM includes the option of cost-optimized charging of BEVs. Besides V1G that optimizes the time and duration of charging depending on the electricity prices and uses BEVs as virtual generation plants, the ESM can integrate 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 (2022) describe the mathematical implementation of the charging strategies in “ISAaR”, the underlying driving profiles, technical parameters, and respective data sources in detail. Wohlschlager et al. (2024) outline 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 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 mainly stem from Kern and Kigle (2022), the scenarios are adjusted to consider a higher average battery capacity of 70 kWh and an additional plug-in probability of 60 % due to recent technical developments, as resulting from discussions with BEV manufacturers.

2.1.2 Assessment Boundaries

The **system boundary** of the assessment is the difference in the construction and operation of energy generation and storage plants needed to cover the energy demand in a smart energy system with large-scale V1G and V2G integration. This also includes plants for energy conversion between energy carriers, as all energy carriers modeled by “ISAaR” are considered in the assessment. Facilities and infrastructure required for energy distribution and final energy demand are not part of the assessment. Due to the temporal resolution of “ISAaR”, energy system expansion is evaluated in five-year-steps from 2025 to 2050. The set geographical scope is the EU of 27 members plus the United Kingdom, Norway and Switzerland. The system expansion in previous years is not relevant within the chosen differential point of view. Moreover, the environmental assessment of the technologies’ end-of-life is not part of this study.

The construction of energy generation and storage plants is assessed as capacities taken into operation within time-steps. Energy plant operation is evaluated as primary energy carrier import to the European energy supply sector and their combustion within conversion processes. Combustion-related emissions of green and synthetic energy carriers are compensated within their production process. The offsetting of residual combustion emissions through carbon capture and storage (CCS) to reach target emissions is included in the pLCA. Figure 2 illustrates the components of the energy supply sector covered by the system boundary.

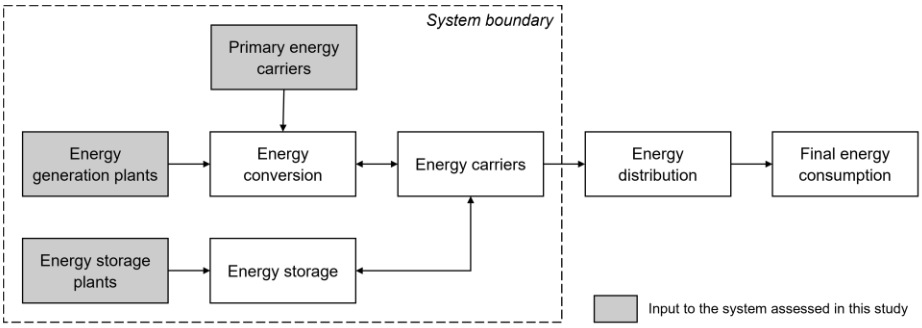

Figure 2: The system boundary of the pLCA is set as the inputs to the energy supply sector, thus covering the overall environmental repercussions of energy system expansion and operation.

Allocation procedures become relevant in LCAs of energy system scenarios, when energy plants can generate more than one energy carrier type, such as combined power and heat generation plants. The impacts then need to be allocated between the different output energy carriers. However, as the defined system boundary includes all energy carriers modeled within “ISAaR”, all impact shares allocated to the individual generation of distinct energy carriers are comprised within the boundary. Consequently, allocation procedures are irrelevant to the present use case.

In both ESM scenarios, the underlying transport model is identical even though BEVs in the “BESS” scenario cannot perform bidirectional charging. As a consequence of the differential system under consideration, the manufacturing of BEVs and their batteries are not included in the system boundary. Nonetheless, the provision of significant flexibility potential through V1G or V2G necessitates the widespread deployment of charging infrastructure capable of bidirectional charging with additional information and communication technologies (ICT). ICT prerequisites for different charging modes including uncontrolled charging, V1G and V2G, are aligned the with German distribution system's standards on communication infrastructure in private households, as described by Wohlschlager et al. (2022), and summarized in Table 1.

Charging infrastructure includes intelligent metering system components and a wallbox. It is possible to operate the wallbox with AC or DC. DC wallboxes are distinctive in that they necessitate more resources than AC wallboxes, granting them a proportionally higher ecological footprint (Wohlschlager et al., 2022).

	Uncontrolled charging	V1G	V2G
Modern metering device (mME)	1	2	2
Smart meter gateway (SMGW)	1	1	1
Wallbox	1 AC	1 AC	1 DC

Table 1: ICT requirements for charging infrastructure for (direct) unidirectional and bidirectional charging as in Wohlschlager et al. (2022).

Based on Table 1, it is possible to derive ICT variations needed for integrating BEVs into the European energy system through V1G and V2G. In alignment with the system under consideration, these variations, i.e., the production of one additional mME for V1G/V2G and the replacement of an AC wallbox with a DC wallbox for V2G only, are used to assess the environmental costs of bidirectional charging. One BEV used for energy system storage is associated with one household with its own charging infrastructure capable of bidirectional charging, thereby implying that infrastructure is not shared between households. Aforementioned differences in ICT infrastructure are thus assessed per 70 kWh of provided storage capacity to the energy system through V1G or V2G. BEV charging through public charging infrastructure is not included in the scope of this study, as charging and discharging in "ISAaR" is performed with 11 kW, a charging power typically found in private charging. BEV battery aging induced by additional charging cycles due to V2G is addressed in the discussion in Section 3.2.

2.2 Inventory Analysis

In this section, a methodology for generating the foreground inventory using "ISAaR", in a first step, and the background inventory using the "ecoinvent" LCI database, in a second step, is outlined.

2.2.1 Foreground inventory

a. Variations in the construction of energy storage and generation capacities

To capture differences between the two scenarios in constructed capacities between modeled time-steps, absolute installed capacities in each evaluated time-step are used. In "ISAaR", installed energy storage and generation capacities are aggregated according to their plant type. In the following, a methodology for calculating variations in constructed capacities between two scenarios is set up. The discussion holds for generation and storage technologies alike.

$\mathcal{E}$ represents the set of modeled “ISAaR” time-steps, such that $\mathcal{E} = t_k \in \mathbb{N}^+$, where $t_k = t_0 + k \cdot T$, $k \in \mathbb{Z}$. t_0 stands for the earliest modeled year, while $T \in \mathbb{N}^+$ characterizes the time gap between two evaluated years. For the assessed ESM scenarios, $t_0 =$ 2025 and $T =$ 5, thus every time-step in $\mathcal{E}$ prior to t_0 lies in the past.

In the following, the installed capacity of any energy plant type i in a scenario s for an expansion year $t_k \in \mathcal{E}$ shall be denoted as $P_{inst}(s, t_k, i)$. The plant type’s increase or decrease in capacity available to the energy system for a year t_k with respect to the previous modeled year $t_k - 1$ can be expressed recursively. This net constructed capacity is defined as:

$$P_{net}(s, t_k, i) = P_{inst}(s, t_k, i) - P_{inst}(s, t_{k-1}, i)$$

Introducing $L \in \mathbb{N}^+$ as being the lifetime of the considered energy plant type i, the modeled time-step the plant type was built in lies $n = \lceil L/T \rceil$ time-steps in the past. Hence, for the evaluated year $t_k \in \mathcal{E}$, the capacity to be dismantled upon reaching the plant type’s end-of-life can be written in terms of a past net constructed capacity:

$$P_{dis}(s, t_k, i) = P_{net}(s, t_{k-n}, i)$$

The sum of net constructed and dismantled capacity for the evaluated year t_k accounts for the actual overall capacity constructed and taken into operation in the time-step. This gross constructed capacity is expressed as:

$$P_{cons}(s, t_k, i) = P_{net}(s, t_k, i) + P_{dis}(s, t_k, i)$$

Now, evaluating the variations in gross constructed energy plant capacities, the two ESM scenarios – “BESS” and “BESS+V2G” – are compared. This variation for any energy plant type i is expressed as the difference in gross constructed capacity between “BESS” and “BESS+V2G”. If “V2G” now represents such differential scenario between the two ESM scenarios, the following equation can be derived:

$$\begin{aligned} P_{cons}(\text{"V2G"}, t_k, i) &= P_{cons}(\text{"BESS+V2G"}, t_k, i) - P_{cons}(\text{"BESS"}, t_k, i) \\ &= \big(P_{inst}(\text{"BESS+V2G"}, t_k, i) - P_{inst}(\text{"BESS+V2G"}, t_{k-1}, i) + \\ &\quad P_{inst}(\text{"BESS+V2G"}, t_{k-n}, i) - P_{inst}(\text{"BESS+V2G"}, t_{k-n-1}, i)\big) - \\ &\quad \big(P_{inst}(\text{"BESS"}, t_k, i) - P_{inst}(\text{"BESS"}, t_{k-1}, i) + P_{inst}(\text{"BESS"}, t_{k-n}, i) - \\ &\quad P_{inst}(\text{"BESS"}, t_{k-n-1}, i)\big) \\ &= P_{inst}(\text{"V2G"}, t_k, i) - P_{inst}(\text{"V2G"}, t_{k-1}, i) + P_{inst}(\text{"V2G"}, t_{k-n}, i) - \\ &\quad P_{inst}(\text{"V2G"}, t_{k-n-1}, i) \end{aligned}$$

As years t_k with $k < 0$ lie in the past, installed capacities in those years are fixed by historical values and cannot differ between the two ESM scenarios. Thus, historical figures for installed capacities are not needed for any energy plant type for computing the variations in gross constructed capacity between both scenarios. In other words, “ISAaR” model results for future time-steps are sufficient for generating the foreground inventory.

Applying the calculation logic to the “BESS” and “BESS+V2G” scenarios, an inventory analysis of the endogenous variations in energy plant capacities expansion stemming from large-scale bidirectional charging implementation can be conducted. Differences in capacities are represented in Figure 3. Thereby, positive values indicate supplementary capacity construction needed in a system with V1G and V2G integration and negative values indicate avoided capacity construction in such a system.

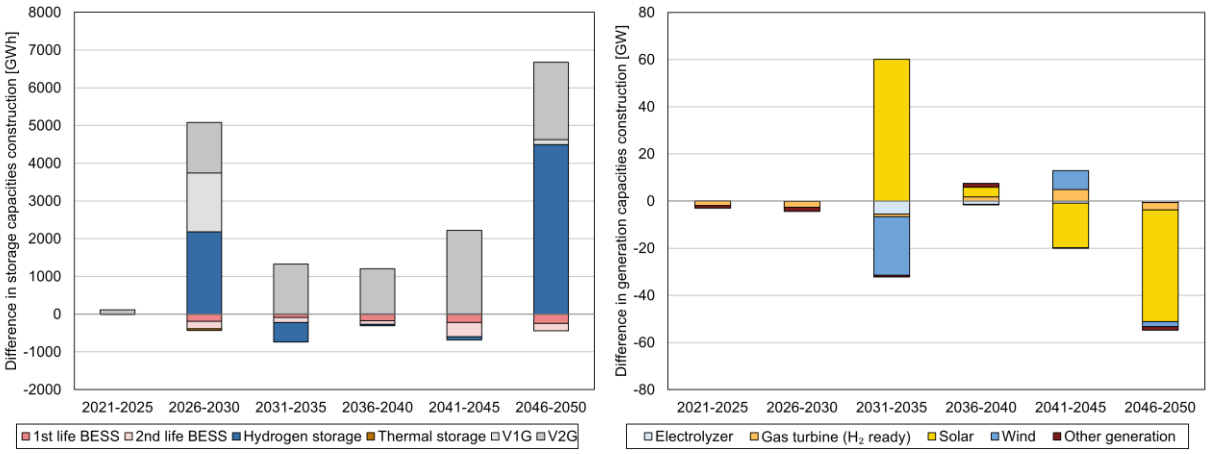

Figure 3: Variations in energy storage (left) and generation plant (right) construction induced by large-scale implementation of V1G and V2G in the European energy supply sector.

For most energy plant types, the differences in constructed capacities are equal or close to zero. However, large-scale implementation of bidirectional charging strategies substitutes stationary 1st life BESS in earlier time-steps and 2nd life stationary BESS in later time-steps. When battery reconditioning procedures reach a higher maturity level and more BEV batteries are available for repurposing upon reaching their end-of-life, 2nd life batteries are, then, prioritized by the “ISAaR” cost-optimization with respect to 1st life batteries because of their lower costs (Global Sustainable Electricity Partnership, 2021; Schmidt-Achert and Pellinger, 2021). In “BESS+V2G”, mainly all battery-based storage requirements are covered by a bidirectional integration of BEVs into the energy system, as BEV integration costs are lower than the costs for BESS (Dossow and Kern, 2022). In this scenario, the maximal potential of BEVs as storage systems is exploited in the cost-optimization.

The ESM model favors the use of battery-based storage in combination with PV electricity provision, as it is cheaper than wind power and its fluctuations more predictable. Large-scale BEV integration in “BESS+V2G” comes with an overall higher storage potential to the energy system, and thus, an earlier deployment of PV capacities. The better integration of RE in “BESS+V2G” further explains the additional construction of hydrogen storage capacity in the time-steps 2026–2030 and 2046–2050, as more electrolysis is performed in hours with low electricity prices.

Overall, variations in generation capacities only make up a few gigawatts (< 1 %) from total installed generation capacities. As for storage capacities, the differences in hydrogen storage represent a few percent (up to 4 %) of the total installed hydrogen storage capacities in later time-steps, from 2036 onwards, but can reach 50 % before that. The differences between the battery storage options are decisive when it comes to electricity storage. Thus, bidirectional charging does mainly have a significant influence on the endogenous storage expansion in the ESM.

b. Variations in primary energy consumption

To model the foreground inventory for energy plant operation, we consider the divergences in the imports of primary energy carriers to the European energy supply sector and in CCS between the two scenarios. The variations in primary energy consumption between the two scenarios are denoted as $E_{demand}(\text{"V2G"}, t_k, j)$ for any energy carrier j for all modelled time-steps t_k from 2025 to 2050. Annual variations are assumed to stay constant within evaluated time-steps. Methodologically, the “ISAaR” ESM outputs the total imports of primary energy carrier types (e.g., green synfuels, fossil oil) to Europe across all energy consumption sectors and the demand in unspecified energy carrier (e.g., liquid hydrocarbons) of each individual sector. Using this information, a ratio between the demand of unspecified energy carriers in the energy supply sector and their total demand in Europe can be calculated. The total imports of each energy carrier type are then allocated to the energy supply sector according to this ratio.

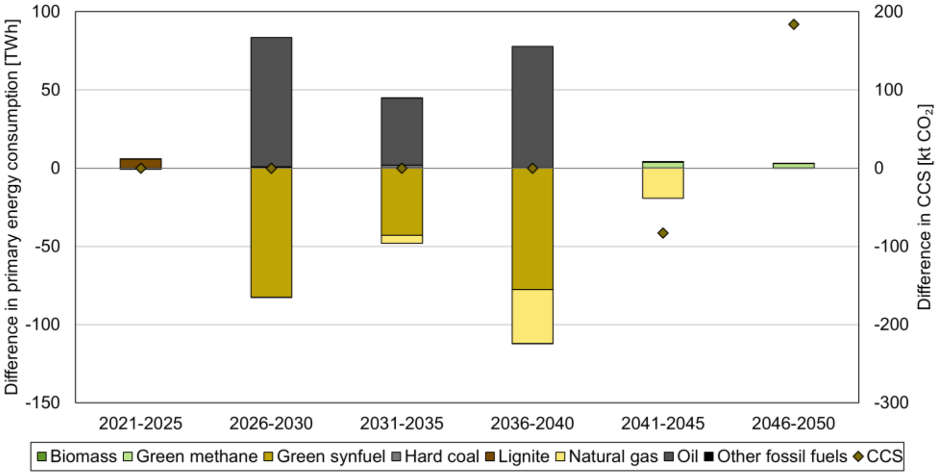

Figure 4: Variations in primary energy consumption induced by large-scale implementation of V1G and V2G in the European energy supply sector.

Figure 4 illustrates the ESM differences in primary energy consumption applied to a system with bidirectional charging integration. Results show that in a system without BEV integration part of the consumption of fossil oil is substituted by the consumption of green synfuel in years until 2040. This part represents less than 3 % of the overall demand in liquid hydrocarbons in those time-steps. The substitution is necessary to reach the emission reduction targets in the “BESS” scenario. Indeed, as seen in the variations in capacities in Figure 3, bidirectional charging enables a better integration of RE due to the higher flexibility provided by BEVs. This leads to an increased use of green hydrogen in conventional generation plants and a decarbonization of the system in the “BESS+V2G” scenario. Thus, in the “BESS” scenario, more green synfuels need to be imported to reach similar decarbonization levels. After 2040, differences remain marginal, but CCS differences occur to meet the emission constraints in the ESM optimization.

Figure 5 shows that the large-scale deployment of bidirectional charging increases the overall amount of electricity supplied by battery storage systems in the future energy system. In “ISAaR”, the output of electricity stored in BEVs has a slightly lower efficiency (94 %) as compared to stationary BESS (95 %). However, in the “BESS+V2G” scenario, the total primary

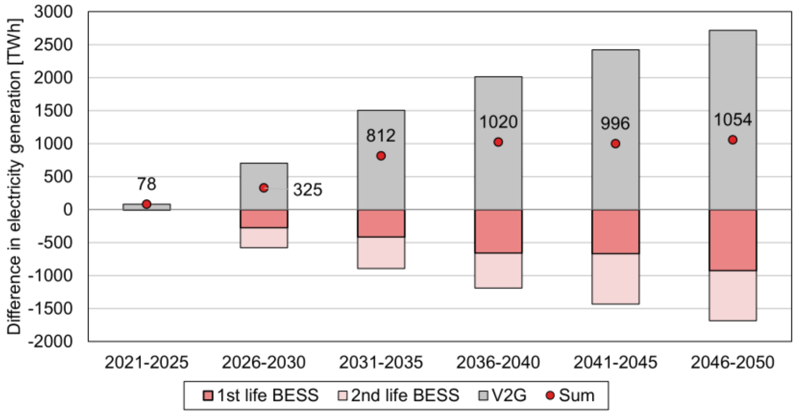

Figure 5: Variations in electricity supply from battery storage systems induced by the large-scale implementation of V1G and V2G in the European energy supply sector.

energy consumption decreases by 43.5 TWh in the time frame 2025–2050. Thus, despite the higher amount of electricity supply from battery storage systems in this scenario, the decrease in efficiency does not lead to an overall increase in primary energy consumption.

2.2.2 Background Inventory

Due to the large number of diverse technologies modeled by ESMs, most studies coupling ESM and LCA, including this one, make use of an LCI database for modeling the background inventory (Laurent et al., 2018). Thereby, issues highlighted by Vandepaer and Gibon (2018), such as technological and geographical resolution disparities and data availability, have been addressed.

We use “ecoinvent” as a basis for the LCI and apply the “premise” tool (Sacchi, Terlouw, et al., 2022) for a systematic, future-oriented modification based on the “REMIND” integrated assessment model (IAM). The socio-economic pathway (SSP) and representative concentration pathway (RCP) are chosen to match the “ISAaR” scenario and climate target assumptions. A SSP2 business-as-usual trend with a collective striving towards keeping global warming under 2 °C (RCP2.6) has been evaluated as the best fit for the “solidEU” scenario. The “REMIND” implementation of this pathway grants a peak budget of 1150 Gt CO_2 in the time interval from 2020 to 2100, after which GHG emissions are required to decrease to meet the set target value (Luderer et al., 2024).

The matching of “ISAaR” technologies with prospective background processes from the LCI database “ecoinvent” can be found in Table 2 in the Appendix. In our case, no disaggregation of background processes is needed, only aggregation, as the ESM technology resolution is lower than the resolution of the LCI database. Aggregation weights are applied considering “ISAaR” technology developments. Double counting of energy plant construction has been addressed within the matching of primary energy carriers. Indeed, in “ecoinvent”, impacts from the construction of generation plants are comprised within the background inventory of primary energy carrier combustion. However, as they are already included within our system boundary, they need to be subtracted from the background impacts of primary energy carrier consumption to avoid double counting.

Background inventories of additional ICT requirements for the BEV charging infrastructure for unidirectional and bidirectional charging strategies are assessed in accordance with the difference in requirements with respect to uncontrolled charging discussed in Section 2.1.2.

BEV battery repurposing into stationary 2nd life BESS is modeled based on the LCI of Schulz-Mönninghoff et al. (2021). In their study, the remanufacturing process of a lithium-ion battery in Europe is assessed including the production and installation of a battery and a power electronics container. The 1st life BESS background inventory is modeled based on the LCA of lithium-ion NCM111 battery production from Dai et al. (2019) and the battery and power electronics container production and installation from Schulz-Mönninghoff et al. (2021). The lithium-ion NMC111 battery chemistry is widely used in BEV storage systems (Camargos et al., 2022) and its GWP impact score is in accordance with the average for this type of chemistry as shown by Gutsch and Leker (2022).

Specific GWP and MD for the production of one megawatt (resp. one megawatt-hour) of energy generation (resp. energy storage) capacity and of the consumption of one megawatt-hour of primary energy carrier are evaluated using the Brightway2 LCA software environment (Mutel, 2017).

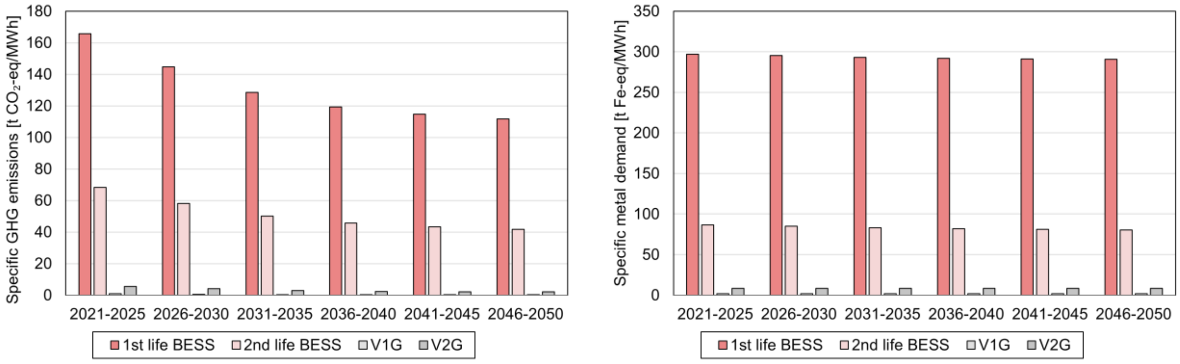

Figure 6: Temporal evolution of the GWP and MD for the provision of one megawatt-hour capacity of flexibility to the energy system.

Results for technologies enabling the flexibilization of the electricity supply are shown in Figure 6. 1st life and 2nd life BESS manufacturing has proportionally high life cycle impacts as compared to BEV storage provision through V1G or V2G. BESS are subject to high GHG emissions and critical metal resource utilization, not only due to battery manufacturing (Dehghani-Sanij et al., 2019) but also due to battery and power electronics container production (Schulz-Mönninghoff et al., 2021). The difference in impacts of 1st life BESS becomes even more pronounced when looking at metal depletion. This is due to their particularly high need for metal resources, including lithium, nickel, cobalt, and manganese. BEV battery manufacturing being outside of the considered system boundary, life cycle impacts of BEV integration through V1G and V2G only comprise additional ICT requirements for the charging infrastructure and, thus, are much lower by comparison. These insights become particularly important in light of the major contributions of battery-storage options to the overall endogenous variations to the energy system between the two ESM scenarios.

3 Results

Multiplying and summing up variations in energy system expansion and specific GWP and MD impact factors (IF), the overall environmental impacts $I(\text{"V2G"}, t_k)$ for time-steps t_k from 2025 to 2050 for each impact category can be evaluated as:

$$I(\text{"V2G"}, t_k) = \sum_i P_{cons}(\text{"V2G"}, t_k, i) \cdot IF_i + \sum_j E_{demand}(\text{"V2G"}, t_k, j) \cdot IF_j$$

The results from the impact assessment are portrayed in Section 3.1, while the influence of battery degradation through bidirectional charging on the results is investigated in Section 3.2.

3.1 Impact Assessment

Figure 7 and Figure 8 show the difference in environmental impacts induced by endogenous energy plant expansion and operation accountable to V1G and V2G services. Figure 9 and Figure 10 highlight the contributors to the differences in GWP and MD, respectively, until 2035 (left) and 2050 (right).

According to the considered scenarios, large-scale bidirectional charging implementation in smart energy systems can enable savings of 54.5 Mt CO_2-eq of GHG emissions and 282.3 Mt Fe-eq of metal resources until 2050 at European level. Thereby, total variations in capacity construction reduce energy system impacts by 97.5 Mt CO_2-eq and 279.1 Mt Fe-eq in that time interval, contributing to 179 % and 99 % to the total impact savings of an energy system with flexible BEV integration. Overall differences in primary energy consumption are found to induce an increase in GHG emissions of 43 Mt CO_2-eq, affecting total GWP savings by -79 %. Their impact on MD savings remains marginal, making up 1 % or 3.1 Mt Fe-eq.

As can especially be seen in Figure 9 and Figure 10, battery-storage options play an essential role for the differences in life cycle impacts. Large-scale V1G and V2G deployment enables

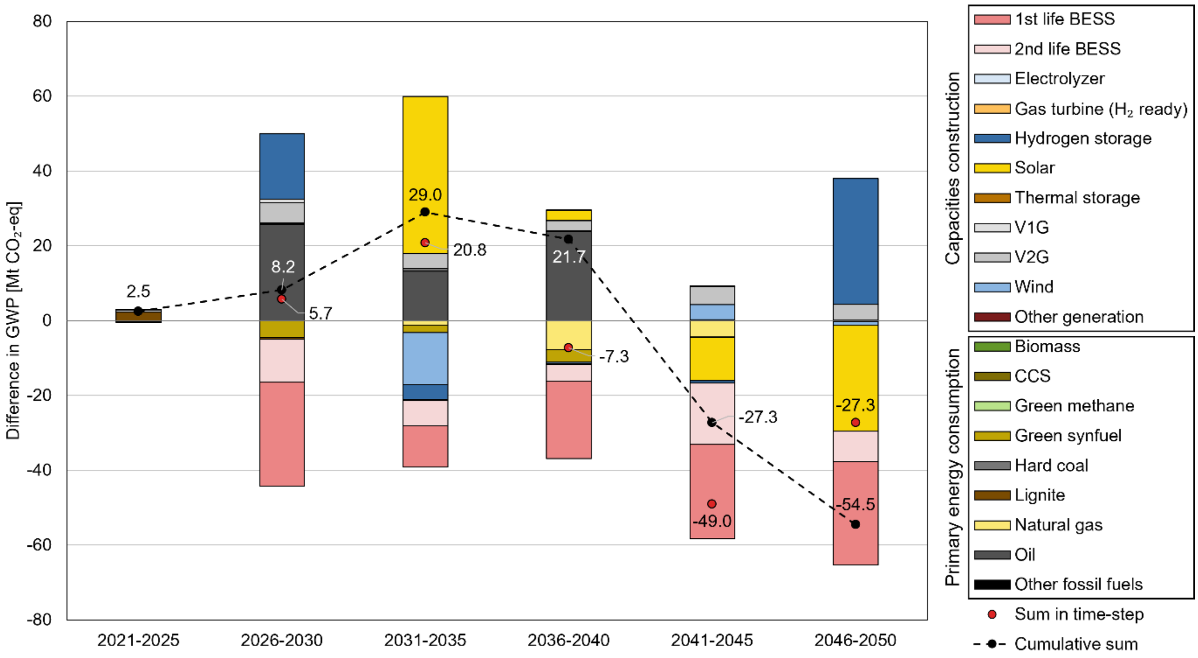

Figure 7: Variations in global warming potential (GWP) induced by large-scale implementation of V1G and V2G in the European energy supply sector.

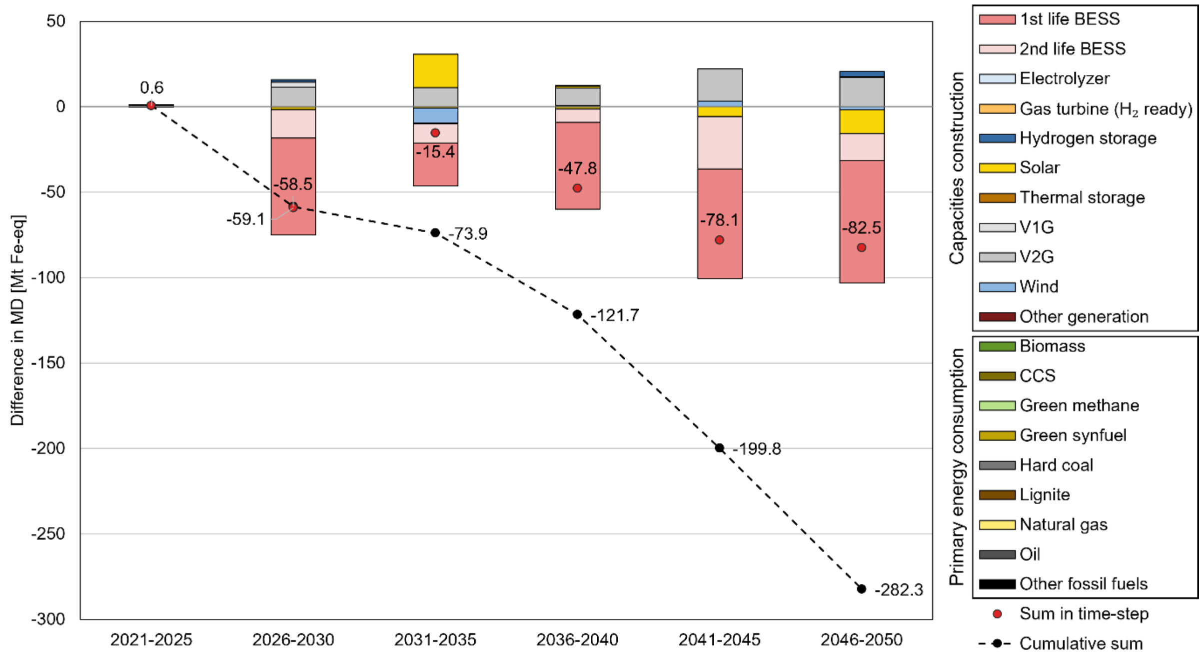

Figure 8: Variations in metal depletion (MD) induced by large-scale implementation of V1G and V2G in the European energy supply sector.

saving 159.5 Mt CO_2-eq until 2050 by avoiding the production of 1st and 2nd life BESS, which represents around 82 % of all savings stemming from impact reduction contributors. This part is even more significant when considering MD impacts, as the share of impact savings of stationary BESS with respect to all impact saving contributions reaches 97 %, or 350.4 Mt Fe-eq. On the other side, Figure 9 and Figure 10 (right) show that the environmental impacts from 2025 to 2050 of upgrading BEV charging infrastructure to be capable of performing V1G and V2G amount to 22.9 Mt CO_2-eq and 69.8 Mt Fe-eq. These figures represent 16 % and 93 %, respectively, of the total additional GWP and MD impact contributions caused by bidirectional charging deployment in the "BESS+V2G" scenario. These findings should nevertheless be considered under the assumption that each BEV capable of performing V1G or V2G uses its own charging infrastructure. By sharing charging stations (public or private), environmental impacts induced by additional ICT requirements might be further reduced.

While bidirectional charging has been found to lead to decreases in the environmental impacts of the energy system in the long term, i.e., until 2050, an increase in GWP can be observed in the medium term, i.e., until 2035 (see Figure 9, left). Indeed, the higher overall available storage capacity provided by BEVs as a flexible storage option for the energy system favors the integration of RE in the medium term. The accelerated construction of PV capacities in years 2031 to 2035 caused by V1G and V2G integration has an environmental cost of 42.0 Mt CO_2-eq and 19.5 Mt Fe-eq in that time-step. On the other hand, as the deployment of stationary BESS grants high individual storage capacities, wind turbine construction in that time interval is slightly increased. The overall ecological impacts of accelerated RE expansion (considering wind and PV) until 2035 is found to be of 28.0 Mt CO_2-eq and 10.9 Mt Fe-eq. Since both scenarios, however, reach the climate targets in the long-term, the effect of bidirectional charging on RE integration is mostly outbalanced by 2050, as shown in Figure 9 (right). Small life cycle impact reductions in wind and PV expansion of 6.5 Mt CO_2-eq and 5.3 Mt Fe-eq can even be observed in 2050.

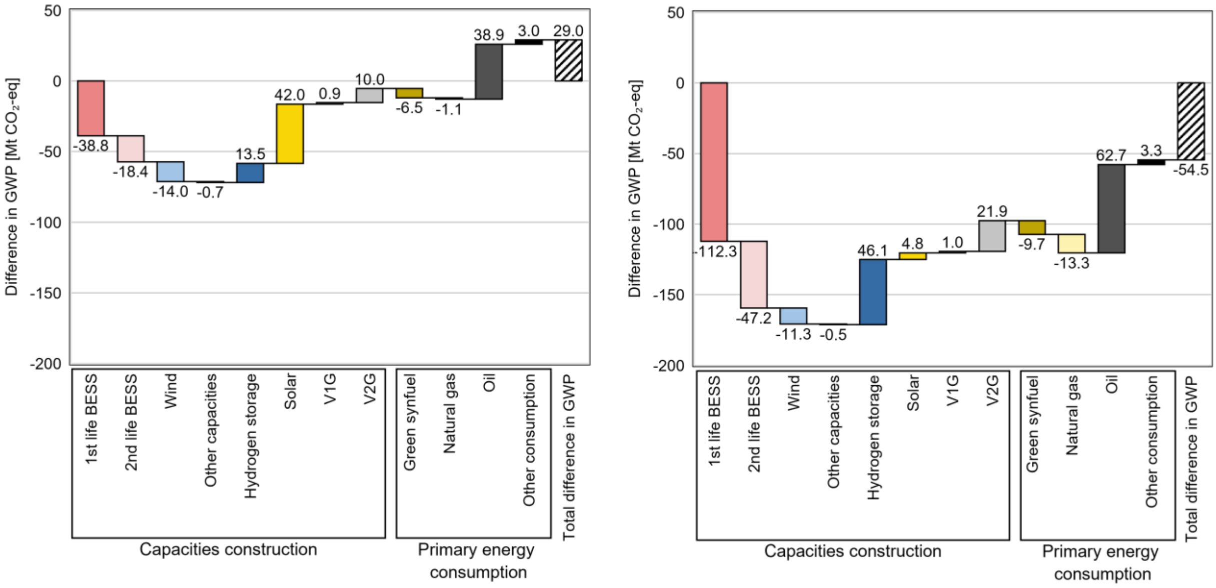

Figure 9: Contributors to changes in global warming potential (GWP) induced by large-scale implementation of V1G and V2G in the European energy supply sector until 2035 (left) and 2050 (right).

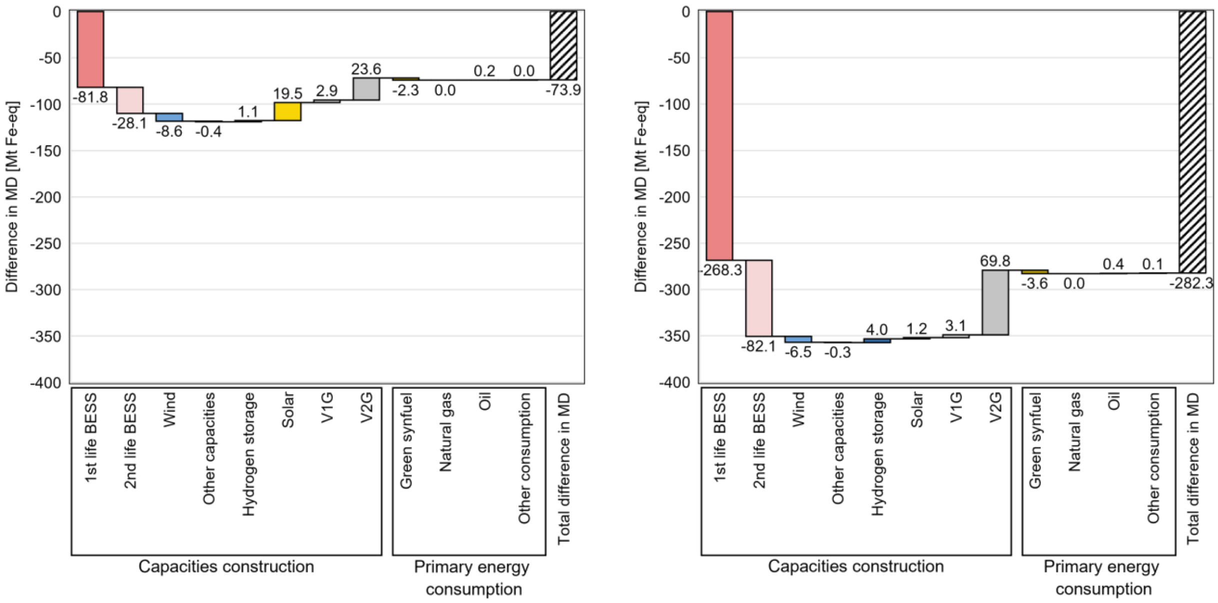

Figure 10: Contributors to changes in metal depletion (MD) induced by large-scale implementation of V1G and V2G in the European energy supply sector until 2035 (left) and 2050 (right).

Furthermore, increased flexibility provision through the bidirectional integration of BEVs into the grid increases hydrogen storage expansion. This leads to an environmental impact of 46.1 Mt CO_2-eq until 2050, as can be seen in Figure 9 (right). Bidirectional charging deployment has also been found to slightly disfavor imports of green synfuels against their fossil equivalent, as green synfuels contribute to reaching the emission targets of the ESM in the “BESS” scenario. Indeed, in the “BESS+V2G” scenario a better integration of RE already contributes to achieving these targets, making the import of expensive green synfuel to this end superfluous. The combustion of fossil oil induced by bidirectional charging leads to an increase in GHG emissions of 62.7 Mt CO_2-eq until 2040 (see Figure 7). Green synfuels combustion in the “BESS” scenario having offset emissions, savings in their consumption in the “BESS+V2G” scenario only amount to 9.7 Mt CO_2-eq, which can be traced back to green hydrogen production.

Due to the underlying scenario assumptions, other changes in energy system impacts are marginal compared to the overall energy system and are majorly ascribable to cost optimization variations of the ESM.

3.2 Sensitivity Analysis: Impact of V2G on BEV Battery Aging

BEV batteries are considered to reach their end-of-life, when their state-of-health (SoH) falls below 70–80 % (Saxena et al., 2015). Calendar and cycle battery aging depend on numerous factors, including but not limited to ambient temperature, plug-in duration, depth of charge and number of charging cycles. V2G is usually said to accelerate battery degradation because of the increase in charging and discharging cycles, which is often regarded as the main concern with this technology (Guo et al., 2019). A review from Etxandi-Santolaya et al. (2023) finds that this additional capacity fade is, however, limited to less than 6 % in the evaluated studies. Some studies even conclude that, on the contrary, V2G could be beneficial for the battery’s SoH, when charging operations are optimized by battery management (Gong et al., 2024; Lehtola and Zahedi, 2021; Zhao and Baker, 2022).

A sensitivity analysis is conducted to evaluate the environmental impact of BEV battery aging induced by the bidirectional operation of BEVs to provide short-term storage capacity in the energy system. Considering findings in literature, a range of ± 5 % has been identified for evaluating the changes in BEV battery capacity fading attributed to V2G with respect to uncontrolled charging. The percentual change is then applied to the overall impacts of BEV battery production. The latter is calculated by multiplying the impacts from lithium-ion NCM111 battery production with the variations in V2G storage capacity in the energy system until 2050. Thereby, we assess the environmental effects of BEV battery aging in that time frame. The impact assessment results with additional consideration of battery degradation are shown in Figure 11.

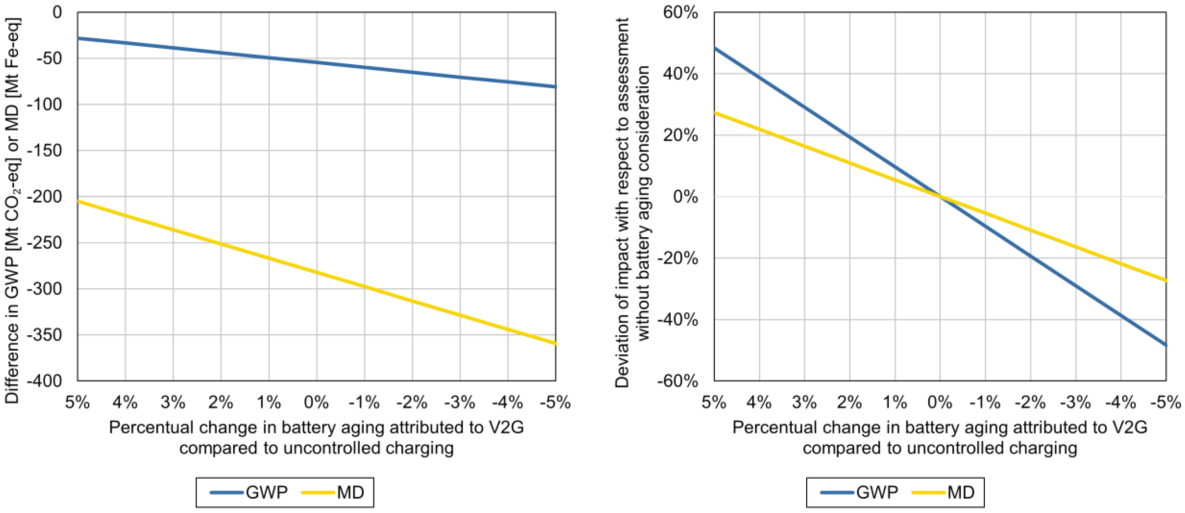

Figure 11: The absolute (left) and relative (right) results evaluate the global warming potential (GWP) and metal depletion (MD) of changes to the energy system from 2025–2050 brought forth by BEV-based electricity storage when considering the effects of V2G on battery aging compared to uncontrolled charging.

Overall savings in GWP brought forth by the bidirectional integration of BEVs in smart energy systems vary from 28.1 to 80.9 Mt CO_2-eq, when accounting for a ± 5 % change in BEV capacity fading. Concerning MD, savings are in a range of 205.2 to 359.4 Mt Fe-eq. Hence, in the considered scope for battery degradation, no sensitivity case has been found to lead to an absolute increase in the environmental impacts of the difference in the energy system until 2050. Relative deviations of impacts compared to the reference assessment case without consideration of battery degradation (0 % percentual change) are in a range of ± 48 % for GWP and ± 27 % for MD.

4 Discussion

In light of the results presented above the outlined research question "**How does the large-scale integration of flexibility potential from BEVs in smart energy systems through bidirectional charging affect the environmental impacts of the energy system?**" is discussed in the following.

Over the investigated time frame between 2025 and 2050, our results show a total reduction of 54.5 Mt CO_2-eq (GWP) and 282.3. Mt Fe-eq (MD) by introducing V1G and V2G technologies in the European energy system. Savings in GWP represent 0.02 % of the combustion-related emissions of the energy supply sector in the EU-27 in 2022 (European Environment Agency, 2024) and, thus, remain marginal compared to current levels. When including changes in battery aging emissions, this share remains minor at 0.01–0.03 %. Regarding MD, Xu et al. (2021) find that around 470 to 2200 Mt Fe-eq of metal resources are needed for decarbonizing the European electricity system by 2050. Our pLCA results make up 13 % to 60 % of this proposed metal demand, or 21 % when looking at the average of the proposed range. Insights on metal savings when considering the fading of BEV capacity through V2G represent 15 to 27 % of that average. While keeping in mind that our scope reaches beyond the power sector, it can be concluded that the deployment of bidirectional charging strategies may confer a noticeable advantage in metal resource preservation attributable to the lesser need for BESS.

Endogenous variations to the energy system accountable to V1G and V2G deployment are found to be small compared to overall expansion and operation. Thus, they are sensitive to the ESM cost-optimization of "ISAaR". Still, it is possible to discern temporal patterns in life cycle impact repercussions due to a large-scale implementation of bidirectional charging in smart energy systems. Concerning GWP, it occasions an increase in GHG emissions in the medium-term due to accelerated PV integration and emissions savings in the long-term. The break-even is estimated to occur around 2042. Concerning MD impacts, however, bidirectional charging is found to lead to a steady decrease in critical metal resource utilization from 2026 until 2050.

Compared to a system without V2G availability, the major difference lies in avoiding the large-scale installation of stationary BESS capacities. Even though overall installed capacities are much higher for BEV-based flexibility, its environmental impact is much lower than BESS-based storage due to savings in battery pack and container production. Additional GWP and MD impacts of ICT production for BEV charging infrastructure are much less significant. The appraisal of life cycle impacts of BEV battery aging accountable to V2G has shown significant alterations of the pLCA results, reaching almost 50 % with respect to the reference impact assessment for GWP, highlighting the importance of the environmental impact of battery production.

Thereby, the system boundary of the pLCA plays a major role in these findings. Due to the underlying transport model being identical in both ESM scenarios, no environmental costs for BEV production have been assessed. However, to be able to provide sufficient flexibility potential, enough BEVs must be in circulation and connected to charging infrastructure simultaneously. Going beyond the scope of "ISAaR" model assumptions, it could be that solely relying on this technology in the future might induce a higher production of BEVs, which further increases electricity demand and the necessary power generation to supply it. This would, consequently, increase the environmental impact of bidirectional charging in smart energy systems. Besides, large-scale implementation of bidirectional charging strategies supposes that incentives towards BEV and bidirectional charging infrastructure ownership are established by governments. Thus, environmental savings elaborated within this work should be faced with the life cycle repercussions of limiting car purchases and travel and promoting sufficiency. On the other hand, in the "BESS" scenario, the ESM notably relies on 2nd life BESS for providing flexibility. Yet, as these are manufactured using repurposed BEV batteries, the same considerations as before play a role in the evaluation of the ecological repercussions of this battery storage technology.

Comparing our results with literature, the study from Xu et al. (2020) proposes a decrease in the GWP of electricity production through V2G integration of 94 Mt CO_2-eq in Europe in 2050. The result from our pLCA lies within the same order of magnitude, albeit a direct comparison is not meaningful due to different system boundaries. On the opposite, Zhao and Baker (2022) find that the prospective GWP and MD of delivering one kilowatt-hour of electricity increases when using mobile BEV-based storage for flexibility provision instead of stationary BESS. Unlike this work, they evaluate the environmental cost of BEV battery manufacture within their LCA, highlighting the key role of the defined functional unit and system boundary.

Considering bidirectional charging through the lens of the BEV instead of the energy system, Sacchi, Bauer, et al. (2022) find that the life cycle impacts of the production of one middle-class BEV with a capacity of 66 kWh lie at 18.5 t CO_2-eq and 13.5 t Fe-eq per BEV. Our results show that it is possible to save 0.005 t CO_2-eq and 0.028 t Fe-eq per kilowatt-hour of BEV storage capacity integrated into the smart energy system V1G and V2G. Hence, 2.0 % of the GHG emissions and 13.9 % of the metal utilization arising from the production of one BEV can be mitigated by a bidirectional use of the vehicle in the energy system.

Limitations to this work include biases created by underlying scenarios, assumptions and data availability. "ISAaR" and "REMIND" projections are not representative of actual future states but are strongly influenced by input parameters, model structure, and optimization methodology. They have been conceived separately, and, thus, a complete congruence between them cannot be achieved. Moreover, the generic "ecoinvent" processes composing the background inventory are not entirely representative of the characteristics of individual "ISAaR" technologies. In reality, impacts differ for distinct energy plants, be it, e.g., because of their industrial construction process, supplied material provenance, or site location. Furthermore, the dismantling of energy plants dismantling as well as the generation and treatment of waste from energy production has been neglected within the scope of the pLCA and could be addressed in future work for a more comprehensive assessment of the environmental impacts of bidirectional charging.

In this study, life cycle impact results are not fed back to the ESM for consideration within the optimization process, which is the main disadvantage of ex-post assessments highlighted by Blanco et al. (2020). However, this is not possible within the chosen differential point of view and would not be relevant in the face of the stated research question.

5 Conclusion and Outlook

This study evaluates the long-term environmental impacts on the European energy supply sector when utilizing BEVs as flexible storage options. It conducts a comparative environmental ex-post assessment of two scenarios from an ESM using a pLCA approach. The novelty of this work lies in the methodology developed for the comprehensive assessment of the ecological repercussions of the integration of V2G or of any other technology into future energy systems. A differential point of view is adopted to analyze the life cycle impacts of the construction and operation of energy plants in the long-term. Prospective modifications of the specific impacts of energy system technologies have been included to account for future systemic and technological developments.

The developed automated Python-based framework has been applied to two net-zero ESM scenarios, whose only difference lie in the possibility of using the available BEV fleet for electricity storage through V1G and V2G. Thereby, it has been found that in a cost-optimized system bidirectional charging provides more short-term flexibility for the electricity grid as compared to less cost-optimal stationary 1st and 2nd life BESS. Replacing BESS, which are characterized by polluting and metal-demand-intensive production processes, with already available BEV-based storage systems enables a decrease in the GWP and MD of the future European energy system, when striving towards deep decarbonization levels in 2050. The long-term benefit of bidirectional charging on preserving metal resources is significant, while its benefit on GHG emission reduction is marginal. On the medium-term (2025 to 2042), emissions are even projected to increase due to accelerated RE capacity construction. Since both scenarios, however, reach the climate targets in the long-term, the effect of V2G on RE integration will be outbalanced by 2050.

For further research, we suggest studying the environmental repercussions of the underlying transport model on the results. By broadening the system boundary to include BEV production, other alternatives for individual mobility, such as car sharing and modal shifting, might lead to new insights for decision-makers on the energy and transport transition. Moreover, the environmental effects of using BEV-based storage systems for other applications, such as vehicle-to-home, could be compared with the V2G scenario. Lastly, markets and technological advances for (bidirectional) BEVs and repurposed BEV batteries are fast-changing. Yet, they are key in the implemented strategies for large-scale electricity storage and new insights might be gained by reevaluating the results in the face of future developments.

Acknowledgement

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Appendix

Technology in the ESM “ISAaR”	Background process from the LCI database “ecoinvent” or literature	Assumption
1st life BESS	Lithium-ion NCM111 battery production from Dai et al. (2019) Battery and power electronics container production and installation from Schulz-Mönninghoff et al. (2021)	Lifetime: 15 years
2nd life BESS	Schulz-Mönninghoff et al. (2021)	Lifetime: 15 years
Electrolyzer	electrolyzer, PEM | GLO | unit	Lifetime: 22 years
Gas turbine (H_2-ready)	gas power plant construction, 100MW electrical | RER | unit	Lifetime: 25 years
Heating rod	auxiliary heating unit production, electric, 5kW | RoW | unit	Lifetime: 21 years
Heatpump	brine-water, 10kW heat pump production | RoW | unit	Lifetime: 20 years
Hydrogen storage	95 %: compressed air energy storage plant construction, adiabatic, 150 MW electrical | RER | unit 5 %: high pressure hydrogen storage tank | GLO | kilogram	Lifetime: 40 years
Offsite solar	52 %: photovoltaic open ground installation, 570 kWp, single-Si, on open ground | RER | unit 43 %: photovoltaic open ground installation, 570 kWp, multi-Si, on open ground | RER | unit 2.5 %: photovoltaic open ground installation, 570 kWp, CdTe, on open ground | RER | unit 20.5 %: photovoltaic open ground installation, 570 kWp, CIS, on open ground | RER | unit	Lifetime: 25 years
Power-to-methane	sabatier reaction methanation unit | RER | unit	Lifetime: 12 years
Rooftop solar	52 %: photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | RER | unit 43 %: photovoltaic slanted-roof installation, 3kWp, multi-Si, panel, mounted, on roof | RER | unit 2.5 %: photovoltaic slanted-roof installation, 3 kWp, CdTe, panel, mounted, on roof | RER | unit 2.5 %: photovoltaic slanted-roof installation, 3kWp, CIS, panel, mounted, on roof | RER | unit	Lifetime: 25 years
Thermal storage	thermal storage system construction, solar tower power plant, 20 MW | RoW | unit	Lifetime: 30 years

V1G	Difference in ICT with respect to uncontrolled charging from Wohlschlager et al. (2024)	Lifetime: 15 years
V2G	Difference in ICT with respect to uncontrolled charging from Wohlschlager et al. (2024)	Lifetime: 15 years Battery aging impacts evaluated from production of lithium-ion NCM111 batteries from Dai et al. (2019)
Wind offshore	100 %: wind power plant construction, 2MW, offshore, fixed parts | GLO | unit 100 %: wind power plant construction, 2MW, offshore, moving parts | GLO | unit	Lifetime: 20 years
Wind onshore	37 %*: wind turbine construction, 4.5MW, onshore | GLO | unit 57 %**: wind turbine construction, 2MW, onshore | GLO | unit 6 %: wind power plant construction, 800kW, fixed parts | GLO | unit 6 %: wind power plant construction, 800kW, moving parts | GLO | unit	Lifetime: 20 years *Temporal evolution of weighting: 2025: 37 %, 2030: 41 %, 2035: 41 %, 2040: 50 %, 2045: 58 %, 2050: 64 % **Temporal evolution of weighting: 2025: 57 %, 2030: 53 %, 2035: 53 %, 2040: 44 %, 2045: 36 %, 2050: 30 %
Biomass	market for biogas | RoW | cubic meter	–
CCS	carbon dioxide, captured from atmosphere and stored, with a solvent-based direct air capture system, 1MtCO2, with heat pump heat, and grid electricity | EUR | kilogram	–
Green methane	methane, from electrochemical methanation, with carbon from atmosphere, using heat pump heat | EUR | kilogram	Subtraction of CCS process Replacement of generic hydrogen by hydrogen produced from 50 % from wind and 50 % from solar power
Green synfuel	syngas, RWGS, Production, for Fischer Tropsch process, hydrogen from electrolysis | EUR | kilogram	Subtraction of CCS process Replacement of generic hydrogen by hydrogen produced from 50 % from wind and 50 % from solar power
Hard coal	hard coal, burned in power plant/PC, no CCS | RER | megajoule	Subtraction of plant construction process: market for hard coal power plant | GLO | unit
Lignite	lignite, burned in power plant/IGCC, no CC | RER | megajoule	Subtraction of plant construction process: lignite IGCC power plant 450MW | RER | unit
Natural gas	natural gas, burned in gas turbine | RER | megajoule	Subtraction of plant construction process: market for gas turbine,

		10MW electrical | GLO | unit
Oil	diesel, burned in diesel-electric generating set | RER | megajoule	Subtraction of plant construction process: diesel-electric generating set production 10MW | RER | unit
Other fossil fuels	diesel, burned in diesel-electric generating set | RER | megajoule	Subtraction of plant construction process: diesel-electric generating set production 10MW | RER | unit

Table 2: Background inventory for the technologies assessed in the ESM “ISAaR”, matched with processes from the LCI database “ecoinvent” and literature, including a description of assumptions.

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