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A methodology for absolute environmental sustainability assessment of batteries: a comparative case study of sodium-ion and lithium-ion battery

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Abstract

Increasing global demand for Li-ion batteries driven by renewable energy transition and decarbonization targets have triggered associated sustainability concerns, including environmental impacts, material criticality, toxicity, and circularity. Sodium-ion batteries, though in the early stage of development and commercialization, are considered a promising alternative given their potential environmental and cost benefits. Assessing sustainability from an absolute sustainability perspective is particularly relevant for emerging technologies to avoid unintended impacts and track their implementation to stay within the planetary boundaries. This study presents a methodology for sustainability assessment of batteries, comparing environmental impacts (LCA results) with the allocated share to estimate absolute sustainability performance. The proposed methodology is illustrated using a comparative case study of a sodium-ion battery (NaNMC type) and a lithium-ion battery (LiNMC type). An economic allocation-based approach has been applied to determine the allocated shares. The high deviation in the sustainability ratio indicates poor performance of current battery production practices relative to planetary boundaries for climate change, abiotic resource depletion, and human toxicity impacts. The absolute sustainability performance is comparable for both batteries, with the highest difference in the case of human toxicity (non-cancer) and abiotic resource depletion. Given the high uncertainty and potential limitations of the economic-allocation-based sharing principle and the data sources, the estimated results require critical evaluation and further investigation (e.g., uncertainty and sensitivity analysis and comparative assessment with multiple sharing principles) for a robust assessment and more realistic interpretations. Potential advantages, challenges, and limitations of the applied methodology are addressed.

Keywords: Absolute Sustainability; Batteries; Planetary Boundaries; Sharing Principles

1. Introduction

The Paris Agreement in 2015 and the establishment of 17 Sustainable Development Goals (SDGs) aim to tackle global sustainability challenges to ensure a sustainable future for humanity [1]. The implementation of SDGs led to a stronger focus on the development of renewable energy technologies to support a sustainable future and highlighted the importance of sustainability assessment across all industrial sectors. The sustainability of existing and emerging technologies remains a crucial factor in global technology and policy decision-making. The rapid demand for electric vehicles and renewable energy generation led to a surge in the demand for battery technologies. The global battery market has seen strong growth in the past decade due to the exponential demand, with lithium-ion batteries (LIBs) having the highest share [2]. Despite the potential benefits, such as higher energy density and wider application, LIBs face challenges of material criticality and

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increased costs as well as associated environmental burdens. Novel battery chemistries (generally referred to as emerging battery technologies or post-LIBs) such as sodium-ion batteries (SIBs) have thus attracted the attention of battery technology developers and policymakers due to their perceived potential sustainability benefits over LIBs, such as lower raw material scarcity and costs, and higher safety [3,4]. Assessing environmental sustainability of battery technologies primarily involves the application of life cycle assessment (LCA) for different battery chemistries, with increasing focus on utilizing primary data [5], end-of-life modeling (e.g., recycling) [6,7], prospective LCA for emerging battery technologies [8], and toxicity [9], but lacks a wider inclusion of planetary boundaries (PBs) and absolute sustainability perspective. Following the introduction of the concept of planetary boundaries (PBs) [10], there has been an increasing interest in the development of various methodologies for absolute environmental sustainability assessment (AESA) to evaluate the environmental performance of human activities against Earth's biophysical limits and monitor the progress towards environmental impacts reduction and resource use in an absolute perspective [11]. This further led to the inclusion of AESA approaches in LCA and the subsequent development of LCA-based AESA methods [12] (e.g., PB-based life cycle impact assessment (PB-LCIA) [13]), as well as their application across different industry sectors (e.g., buildings [14], food processing [15]), and scales (e.g., product, industry, and cities) [16,17]. AESA is becoming more relevant, particularly with the increasing evidence of declining planetary health due to the transgression of multiple (six out of nine) PBs [18].

Despite the critical relevance of battery technologies to the current global transition towards sustainable energy and mobility and their rapid technological development, there has been a limited emphasis on the application of AESA approaches in environmental assessments of batteries. In the literature, AESA has been performed on electric automotive batteries in the context of electrification of the French private car fleet [19]. The study tested three sharing principles using a prospective LCA approach to understand the impacts of different decarbonization scenarios. A stepwise approach integrating top-down factors (PBs, IPCC carbon budgets, and sharing principles) for estimating product targets and bottom-up methods for determining product impacts (e.g., LCA, model-based technology assessments) for AESA of electric vehicle batteries has been developed [20]. The study proposed the allocation of carrying capacity (referred to as product targets) to the individual component level to enhance decision-making. A technology roadmap to stay within PBs has been proposed for German electric vehicles by considering three perspectives (consumption, functionality, and product) [21]. It's crucial to explore AESA for current and emerging battery technologies for achieving SDGs (specifically SDG7 affordable and sustainable clean energy for all) and track their absolute progress. Despite all the developments, there has been a limited discussion on sector-specific allocation methods as well as the relevance of allocation approaches for different stakeholders at different product life cycle stages and Technology Readiness Levels (TRL) in the value chain. For example, different stakeholders in the case of batteries include technology developers, policymakers, industry decision-makers, and society etc. In this direction, recent attempts include the development of the "*Fulfillment of Human Needs*" (FHN) sharing principle based on the importance of the product/sector for the users [22] and evaluation of sector-level policies relative to PBs [23]. Considering the data requirements for AESA and associated (high) uncertainties resulting from the data gaps, proposing a methodology at the product/technology level would be more relevant, given the availability of a vast number of published studies on the LCA of batteries. LCA-based AESA also provides the flexibility to accommodate diverse impact categories in the assessment as compared to other approaches for the allocation of global carrying capacities to product or industrial sector level. This paper presents an AESA methodology applicable at the product/technology level for batteries with a broader goal of its further integration with other critical sustainability aspects (social impact hotspots, raw material criticality, circularity), aligning with multi-perspective prospective life cycle sustainability assessment [24]. The proposed methodology is demonstrated using a comparative case study of NaNMC SIB and LiNMC LIB. The potential advantages and limitations of the proposed methodology and its implementation are discussed, along with the future work for further development.

1.1. Background

Performing an AESA involves comparing the environmental impacts of an anthropogenic system to the share of carrying capacity allocated to the product/technology to assess the product system's performance relative to the PBs. This is generally expressed in terms of absolute sustainability ratio or distance-to-target. The absolute sustainability ratio (ASR) is defined as the ratio of the environmental impact of a product to the assigned carrying capacity for the selected impact category [25], where ASR less than or equal to 1 is interpreted as sustainable, and more than 1 as not sustainable (or exceeding PB). Two types of impact assessments can be applied for the calculation of environmental impacts using LCA to perform AESA: 1) PB-based LCIA method [13], and 2) results from conventional LCIA methods translated to PB metrics [26,27]. Multiple allocation approaches have been developed to assign the share of global carrying capacities to different scales (e.g., product, industry, etc.), generally interpreted as allocated share of safe operating space (SoSOS). Ten widely used sharing principles (also referred to as allocation methods) are identified in the literature, which are developed based on distributive justice theory (egalitarian, inegalitarian, prioritarian, or utilitarian) [28]. The predominant practiced choice for AESA has been the climate change impact category due to its globally determined (and accepted) carrying capacity according to the 1.5-degree climate goal as per the Paris Agreement [29]. There have been attempts to determine other environmental impacts (e.g., chemical pollution) as well as social impacts. The need for prioritization of cumulative environmental impacts beyond carbon emissions relative to planetary boundaries has been recognized in literature [30,31].

2. Proposed AESA Methodology for Batteries

A step-wise AESA methodology adopted for specific products/technologies is proposed (Fig. 1). The selection of allocation methods has been kept flexible to accommodate the diverse assessment requirements (goal and scope).

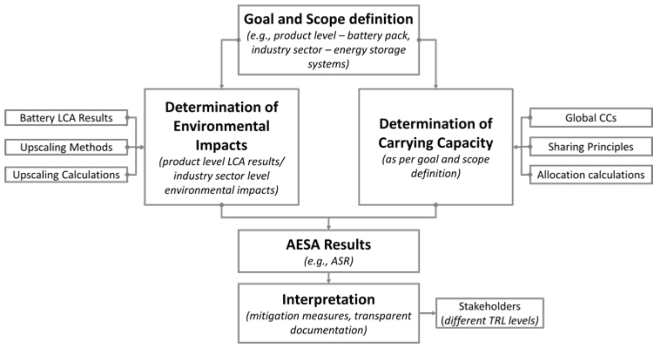

Fig. 1. A generic AESA methodology contextualized for batteries (based on LCA-based AESA [28])

2.1. Determination of Environmental Impacts

LCA is a widely used standardized method for estimating the environmental impacts of batteries. Given the extensive number of published studies covering diverse battery chemistries and system boundaries, LCA results provide a reliable source for acquiring product-level environmental impacts of existing and emerging battery technologies. For case studies focusing on a specific industry sector (e.g., transportation) or application of batteries (e.g., energy storage), the environmental impacts can be upscaled considering relevant factors. For example, in the case of electric vehicles, factors such as battery mass, number of electric vehicles, and vehicle lifespan were considered for the case study on French private car fleets mentioned earlier [19].

2.2. Determination of Carrying Capacities

Multiple estimates of carrying capacity for different PBs have been proposed using different calculation methods and incorporating different impact categories depending on the level of application (product level, national level, or sub-national level). Other estimates include carrying capacity calculations for climate change based on Integrated Assessment Models (IAMs), though such estimates are limited to greenhouse gas emissions, categorizing the boundary definition as either static or dynamic [29]. A widely followed source for estimating carrying capacities for EU aligned with LCA impact categories was proposed by S. Sala et al. [26], developed based on the Environmental Footprint (EF) LCIA method. This represents an extension of earlier estimates based on the ILCD LCIA method [27]. An important point to consider while using the values from these studies is the consistency between the estimated impacts (generally LCIA metrics) and the PB metrics. In the case of inconsistent units, the study [26] provided conversion factors for translating the impacts from other LCIA methods.

2.3. Allocation of Carrying Capacities

Assigning the global carrying capacity can be based on different sharing principles. At the technology/product level, a two step-approach has been suggested: 1) downscaling the global carrying capacity to individual level, and 2) allocating the share estimated in the previous step (using upscaling methods) to the desired (higher) level (e.g., industry sector, organizations, or products). There is no consensus on the fair allocation of the carrying capacities to product-level impacts due to the involvement of subjective judgements in the underlying allocation principles. Using a combination of multiple sharing principles (e.g., equal per capita, responsibility, grandfathering, and ability to pay) has been suggested to determine the SOS at the national level [12].

2.4. AESA performance calculations and Interpretation of results

The calculated ASR value indicates the absolute sustainability performance of the studied system. The deviation in the ASR value from 1 is interpreted as the magnitude of impact mitigation measures required in the system's value chain for it to become sustainable relative to PBs. This interpretation can be utilized for various identifying potential environmental impact hotspots across the supply chain. Further, the effect of different mitigation options on the ASR value can be estimated using a scenario analysis. Using absolute sustainability interpretations of environmental impacts could be more relevant for policy decision-making, and the general public as compared to the conventional LCA results, as PB-based assessments are increasingly cited in the policy frameworks [12,31]. However, as for conventional LCA, clear documentation and transparent communication of the assessment methodology are crucial to understand the sensitivity of estimated results [32].

3. Case Study Description

The application of the proposed methodology has been discussed for a case study of NaNMC SIB and LiNMC LIB. The goal of the case study is to compare the absolute environmental sustainability performance of potential alternative battery technologies on a product level. It aims to demonstrate the application of the proposed methodology and identify challenges in its implementation.

3.1. LCA of Batteries

The case study on NaNMC 111 SIB and LiNMC 622-C LIB were selected with a FU of 1kWh of electricity converted by battery cells over the lifetime, considering cradle-to-gate scenario (material extraction to production) at cell level [33]. The impact categories considered include climate change, abiotic depletion, acidification, human toxicity – cancer and non-cancer, and ozone depletion, and the ILCD LCIA method was used for impact assessment. The study considers primary and secondary data for impact calculations, using ecoinvent

3.7.1 as background database and with a few assumptions on the aggregated material extraction data. The assumed energy density for SIB and LIB are 136.31 Wh/kg and 272.114 Wh/kg, respectively. The calculated environmental impacts are provided in Table 1.

Table 1. LCA results converted per kWh for NaNMC SIB and LiNMC LIB on cell level [33]

Impact Category	Unit	SIB	LIB
Climate Change	kg CO_2 eq	86.653	44.804
Abiotic Depletion	kg Sb eq	0.0362	0.0317
Acidification	mol H^+ eq	0.9903	0.4508
Human Toxicity, Cancer	CTUh	3.89E-05	2.10E-05
Human Toxicity, non-Cancer	CTUh	7.70E-05	8.30E-05
Ozone Depletion	kg CFC-11 eq	1.154E-05	4.95E-06

3.2. Allocation of Carrying Capacity for Batteries

One of the widely used economic allocation methods is selected for the case study. It involves downscaling the global SOS for a PB to individual's share (equal per capita) and then upscaling it to estimate the allocated share of SOS (SoSOS) for a particular product or system (economic allocation). For the current case study, the downscaled carrying capacity per capita estimates are sourced from S. Sala et al. (2020) [26] (Table 2). For the estimation of allocated share, the economic allocation approach proposed by Brejnrod et al. and Ryberg et al. has been used [14,32]. The method first distributes the global carrying capacity on a per capita basis for all human activities and then utilizes product price as a proxy for the utility of the product (with an underlying assumption that economic value acts as a proxy for human wellbeing), hence estimating product's impacts proportional to its price. A potential limitation of the economic allocation approach is that it assigns equal weightage to all impact categories, which may lead to non-optimal allocation of different impacts [14].

Table 2. Carrying capacity estimates used for the case study

Impact Category	Indicator	Carrying Capacity	Unit	Source
Climate Change	Radiative forcing as GWP100	6.81E+12	kg CO_2 eq	[27]
Abiotic Depletion	ADP ultimate reserves	2. 19E+08	kg Sb eq	[34,35]
Acidification	Accumulated Exceedance	1.00E+12	mol H^+ eq	[36]
Human Toxicity (Cancer)	Comparative Toxic Units for Humans	9.62E+05	CTUh	[37]
Human Toxicity (non-Cancer)	Comparative Toxic Units for Humans	4.10E+06	CTUh	[37]
Ozone Depletion	Ozone Depletion Potential	5.39E+08	kg CFC-11 eq	[27]

The impact category-wise allocated share and the ASR is calculated using the following expressions:

$$\text{Allocated Share} = \frac{1}{\text{Global Population}} * \frac{\text{Product Price}}{\text{Country GDP per capita}} \quad (1)$$

$$\text{ASR} = \frac{\text{Product Environmental Impact}}{\text{Allocated Share} * \text{Carrying Capacity}} \quad (2)$$

The data on global population and GDP per capita is taken from publicly available data sources and existing estimates [38,39] and is estimated as 7,954,448,391 and 44,190€ for the year 2021. The production costs of batteries are sourced from published literature for the same year, estimated as 97.94€/kWh (average values reported for the reference year 2021) and 223 €/kWh for NMC type LIB and SIB, respectively [40,41].

4. Results and Discussion

4.1. AESA Results

The calculated AESA results are presented in Table 3. The results indicate the AESA performance of selected SIB and LIB for climate change, resource use, human toxicity, acidification, and ozone depletion. Given the applied allocation method, all impact categories show noticeably high deviation for both batteries, except for acidification and ozone depletion, which is interpreted as unsustainable performance relative to PBs. For example, the production of both batteries utilizes very high carrying capacity in the current scenario for abiotic depletion impacts. This indicates an urgent requirement for reduced resource use and better end-of-life management through more recycling and circular design of batteries. It is important to highlight that using a different SIB chemistry, e.g., Prussian blue analogues would lead to a completely different picture.

Table 3. AESA performance of LIB and SIB

Impact Category	Allocated SoSOS (SIB)	Allocated SoSOS (LIB)	ASR (SIB)	ASR (LIB)
Climate Change	4.32E+00	1.90E+00	20.06	23.61
Abiotic Depletion	1.39E-04	6.10E-05	260.50	520.18
Acidification	6.34E-01	2.79E-01	1.56	1.62
Human Toxicity (Cancer)	6.10E-07	2.68E-07	63.79	78.38
Human Toxicity (non-Cancer)	2.60E-06	1.14E-06	29.59	72.69
Ozone Depletion	3.42E-04	1.50E-04	0.034	0.033

4.2. Discussion

It is crucial to mention that current results for NaNMC SIB and LiNMC LIB are based on theoretical values and do not allow to make statements on the general sustainability of sodium-ion batteries. Rather, more use cases considering different SIB, as Prussian Blue and its analogues, polyanionic compounds (NaMVP ($Na_4MnV(PO_4)_3$)) and other layered transition metal oxides (e.g., $Na_{1.1}(Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05})O_2$ and ($Na_{2/3}(Mn_{0.95}Mg_{0.05})O_2$) should be compared with state of the art LIB. The high variation in the ASR values can be further explored with an uncertainty and sensitivity analysis considering various factors resulting in the variation. A generic framework for assessing parameter uncertainties in the quantification and downscaling carrying capacities has been proposed [42]. Full product life cycle considerations are crucial for more realistic estimates of use phase, lifetime, and end-of-life. The demonstrated assessment currently included the static predefined PB, which can be further extended to analyze mitigation pathways based on the dynamic carrying capacities. Future studies must also utilize dynamic PBs for more robust assessment and reliable decision-making [29]. Evolving methodologies also attempt to address current limitations by including the time dimension in AESA [43]. In this direction, the potential of prospective LCA methods could be leveraged for assessing the impacts of technologies in the early stage of development. A detailed comparison of ASR values estimated using different allocation methods or their combination could yield more meaningful results. It is important to mention that the suggested future directions also add to various methodological challenges and high data uncertainty. Despite these challenges, AESA results can help relevant stakeholders to benchmark their products (a new battery cell) or processes (mining process) against PBs and support effective decision-making. Sector-specific guidelines are currently lacking for identifying suitable allocation methods; such guidelines would require consensus amongst different stakeholders in the value chain. Limited studies for specific products with specified assumptions make it challenging to validate the estimated shares and ASR values. Economy-wide adoption of AESA methods with consensus on allocated shares would yield more effective outcomes.

5. Conclusion and Outlook

The study proposes an AESA methodology for batteries and demonstrates its application for a comparative assessment of LIB and SIB. Despite the weak rigor in the current implementation of the proposed methodology, the importance of absolute assessments is immense and requires additional efforts for further development. AESA is crucial, especially for battery technologies that will play a critical role in achieving the SDGs. The currently followed AESA methods commonly face challenges regarding fairness, subjectivity, and uncertainty. Future studies should further consider social dimensions (e.g., utilizing doughnut economics) by allocating the just boundaries along with the PBs for more realistic estimates and interpretations [44]. Accommodating regional differences for specific recommendations, especially for regionally relevant impact categories (e.g., water use), would add value to the AESA interpretations. It is also crucial to understand the relevance of such assessments for different stakeholders at different TRLs in the value chain. It would be interesting to compare the stakeholder's interpretation of results from a conventional LCA with an AESA study to understand the usability of AESA assessments. Given the global relevance of battery technology development with increasing demand as well as production, a more structured methodology needs to be developed with consensus amongst various stakeholders for wider adoption. The trade-offs amongst mitigation options for different impact categories are crucial to understand, especially for categories such as resource use that are quite relevant for batteries due to the current recycling and material criticality challenges. The current study serves as a basis for further development of an AESA methodology for battery technologies to integrate stakeholder interaction in the methodological developments. Future work would aim to perform comparisons based on similar battery chemistries. Further, determining and integrating social and economic carrying capacities for the selected case study and evaluating the trade-offs amongst different mitigation options would lead to a more comprehensive life cycle sustainability assessment from an absolute perspective.

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