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31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Developing a Methodological Framework for Assessing Absolute Sustainability in Battery Upscaling within Planetary Boundaries

Téo Lavis^{a,b,*}, Rémy Panariello^a, Fabien Perdu^a, Sébastien Rolère^a, Peggy Zwolinski^b

^aUniv. Grenoble Alpes, CEA-Liten, 17 rue des Martyrs, F-38054 Grenoble, France

^bUniv. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 46 Avenue Félix Viallet, 38000 Grenoble, France

* Corresponding author. Tel.: +33 4 38 78 05 65. E-mail address: teo.lavis@cea.fr

Abstract

The electrification of transportation has accelerated greatly in recent years with the support of policymakers. However, this transformation raises the crucial question of the sustainability of such a change. In parallel, the concept of Planetary Boundaries has recently emerged as a framework for quantifying the human pressure on the Earth System. A real interest in applying the Life Cycle Assessment methodology in relation with the Planetary Boundary framework is growing to evaluate the absolute sustainability of products or services. In fact, this could be an opportunity to establish sustainable thresholds for each technology that should not be exceeded. This paper aims to develop a methodology for evaluating the absolute sustainability of the deployment of batteries in the context of the electrification of the French private car fleet. Several sharing principles are used for assigning a Share of the Safe Operating Space, and a prospective LCA is conducted based on different de-carbonization pathways. As a result, this work will provide insights into the development of a go/no-go strategy for the ecodesign and the upscaling of the electric batteries in a prospective perspective.

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Keywords: Electric vehicle; Life Cycle Assessment; Absolute Sustainability; Planetary Boundaries; Safe Operating Space

1. Introduction

Assessing sustainability is becoming critical to build a transition to more responsible production and consumption. The Planetary Boundary (PB) concept was developed to address this issue in 2009 [1], and then revised in 2015 [2] and very recently [3]. Nine boundaries, based on clear scientific basis, were established as quantitative thresholds that should not be exceeded to maintain the Earth System in a stable Holocene state. Therefore, this framework defines a Safe Operating Space (SOS) for humanity to evaluate the risk of the anthropogenic pressure on environment. The PB approach has seen a growing interest in the literature, since it is the opportunity to define a reliable and operationalized methodology for the Absolute Environmental Sustainability Assessment (AESA) by allocating the PBs to products and services [4]–[6]. The idea underneath is to be able for a company to determine ‘how good is a technology, instead of

how best is a technology’ [7], [8]. This should provide tools for decision-making and for ecodesign.

1.1. Integrating PBs into LCA

The evaluation of the environmental impacts in AESA is usually quantified with Life Cycle Assessment (LCA), leading to what Bjørn et al. (2020) call a ‘LCA-based AESA’ [9]. The transfer of LCA methodology through the PB framework is not immediate. Either Life Cycle Impact Assessment (LCIA) could be translated into PBs metrics, namely a PB-based approach [10], or PB can be turned into LCA metrics, to develop a LCIA-based method, as done by Sala et al. (2020) for the impact categories of the Environment Footprint (EF) LCIA method [11]. In total, Ryberg et al. (2016) listed 6 challenges to be tackled to adapt

the PB to LCA [12]. One crucial point is in the definition of a Share of the Safe Operating Space (SoSOS), which refers as the transcription of the PB for a product or a service. This downscaling is usually performed by applying sharing principles, that can be related to distributive justice theories: non-egalitarian sharing considers the environmental burden should not be equally distributed, whereas egalitarian preaches rather for an equitable repartition, based on resources or on welfare [13]. On the other hand, the prioritarian approach allows a positive discrimination for the disadvantaged and the utilitarian ethic aims to increase the well-being in society [9]. When assigning a SoSOS to an industry sector, the distribution target remains the individual human beings, and thus, each choice of sharing principle underlies distributive ethics and should be documented and deliberated before applying an AESA study [13]. Numerous authors highlighted the high sensitivity to the choice of sharing principles [6], [9], [12]–[15] and research on this topic is currently ongoing [14]. Several studies tried to perform PB-LCAs to specific sectors or products. Sandin et al. (2015) studied the textile sector in regard with six PBs and the existing impact categories in LCA with four different ethical principles. Brejnrod et al. (2017) used carrying capacities for evaluating the sustainability of building with two approaches for the sharing principles [16]. More recently, Ryberg et al. (2018) performed a PB-based LCA on a laundry washing operation at the European Union level by integrating multiple sharing principles and conducting a sensitivity analysis.

1.2. A fast electrification of the transport

Although many studies assessed the environmental impacts of the manufacturing of Lithium-ion batteries (LIB) [17]–[23], or the cradle-to-grave impacts of the whole electric vehicle (EV) [24]–[28], none has performed a LCA-based AESA for the battery industry sector yet. Yet, road transport is a major source of emissions, responsible for over 11.9% of global greenhouse gases (GHG) [29]. The electrification is seen as a promising way to decarbonize the personal car fleet, and is highly supported by policy-makers. Therefore, this sector is expected to grow very quickly in the years to come, with a forecasted annual increase of the production of 25% by 2030 exceeding a market size of 4.7 Terawatt hours [30]. Thus, this paper aims to apply the PB framework to evaluate the absolute sustainability of electric automotive batteries, in the context of the electrification of the French private car fleet. Three sharing principles are explored under a prospective LCA to evaluate the sensitivity to the three different Shared Socioeconomic Pathways (SSP).

2. Methodology

2.1. Case study: electric automotive battery

The study focuses on the upscaling of electric batteries for the electrification of the French personal vehicle fleet. The functional unit (FU) can be stated as follows: the battery fleet should “provide the energy to perform an urban profile during one year for all the automotive French fleet of personal electric vehicle.” This is in line with the

recommendations of the IPCC Handbook [31]. The usage profile considered urban driving sequences, based on the ARTEMIS driving cycles [32] for a total of 18879 km per year. The LCI is based on the bill of materials obtained from the whole disassembly of a commercial small electric car, with a 33.3 kWh battery that contains prismatic $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$ (NMC111) cells. The scope of the study includes the whole battery pack, but also the power electronics, and the overconsumption due to the own battery mass. A cradle-to-grave approach is considered. The battery is supposed to be recycled, following the hydrometallurgical LithoRec process described in [33].

As detailed in Lavissee et al. (2023) [34], the LCA is combined with a performance model of the battery, which consists in a combination of an electrothermal model and an aging model. As a result, the battery lifespan and the total energy delivered by the battery can be predicted: the End of Life (EoL) occurs when the battery cannot perform the usage profile anymore, i.e. when the energy or the power are insufficient. The EoL is considered to have occurred when one of the following three conditions is met: (i) cell voltage goes below 2.7V, (ii) the State of Charge (SoC) reaches 0% during the usage profile, (iii) the State of Health (SoH) is under 80%. Under these assumptions, the battery lifespan is calculated to be 12 years, with a mean consumption of 0.1962 kWh/km. As recommended by Ryberg et al. [10], the elementary flows are given in kilogram per year using this lifespan in Equation (1) as the denominator. Besides, as explained by the authors, the large scale considered in the FU reduces the assumptions necessary for allocating the PBs to only one individual product and makes easier the interpretation of results. The upscaling is conducted considering the French fleet of private vehicles is built with the same batteries as the modelled one. Therefore, the reference flow R_f is given by Equation (1):

$$R_f = \frac{\text{mass}_{\text{battery}} \times \text{number of EVs}}{\text{lifespan in years}} \quad (1)$$

2.2. AESA methodology

A LCIA-based approach is chosen for performing the AESA, following the values of Sala et al. 2020 on the EF method [11]. This study will focus on the Climate Change indicator but the methodology shall be applied for the other impact categories for a complete and meaningful AESA. The $\text{SoSOS}_{\text{PB,SP}}$ of one PB with one sharing principle (SP) can be computed according to Equation (2) that comes from [6]:

$$\text{SoSOS}_{\text{PB,SP}} = \text{SOS}_{\text{PB}} \times \alpha_{\text{PB,SP}} \quad (2)$$

With the SOS_{PB} , the safe operating space assigned for one PB, and $\alpha_{\text{PB,SP}}$ is the share of the PB allocated to one industry sector according to the chosen sharing principle. Three sharing principles, following several ethical norm, are applied as recommended [4], [10]. See Appendix A for further details on formulas. The ‘*statu quo*’ is a non-egalitarian principle that considers the distribution of emissions should remain the same in the future. The global GHG emissions reached 55.3 Gt CO_2eq in 2019 [35]. Besides, in the carbon footprint of a French inhabitant, the individual car accounts for 2.03 t CO_2eq /year. Besides,

EVs represent less than 1% of the French passenger car fleet and assuming battery accounts for 30% of the GHG impacts of the whole vehicle, based on [25], the α coefficient is equal to $7.69e-6$. Assuming the SOS for Climate Change (CC) is equal to $6.81e12$ kg CO₂eq with the EF method [11], the $SoSOS_{CC}^{statu\ quo}$ is equal to $5.24e7$ kg CO₂eq/year. In a similar approach as Heide et al. (2023) and Ryberg et al. (2018) [6], [14], a combination of an egalitarian and an utilitarian ethics is applied. This sharing principle, referred as '*FRCap+FCE*', is defined as the ratio of the French population (67 441 850 French inhabitants [36]) compared to the global population, ($7.821e9$ inhabitants [37]), multiplied by the individual expenses for batteries, using the final consumption expenditure (FCE). The French household expenditure dedicated to the personal vehicle contributes 12.5% of the total of 147 billion euros in 2020 [38] and the battery accounts for 26.7% of the total cost of an urban compact EV (*CEA data*). Finally, a sharing principle called '*FCE only*' is explored, which is based solely on the FCE for the battery sector and the global FCE. The first two lines of the Table 1 summarizes the values for those three reference SoSOS.

2.3. Scenario and sensitivity analysis

To assess the long-term sustainability of a battery design a prospective LCA is also conducted to evaluate the absolute environmental impacts of upscaling batteries to the whole fleet at a certain time horizon, depending on several socioeconomic decarbonization pathways. The foreground data (technology, process, location) remains similar, but the background database is updated to align with several Shared Socioeconomic Pathways (SSP), which describe “plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change” [39]. The pathways differ in the narrative of the future society they described. This study examines the SSP1, SSP2, and SSP5 pathways to provide an overview of the best, moderate, and worst-case scenarios. The SSP1 assumes a sustainable path and a development of the human well-being. The SSP5 forecasts a rapid growth driven by fossil fuels while the SSP2 is a less optimistic scenario based on historical trends [39]. These SSP scenarios are combined with mitigation targets in the form of radiative forcing levels, also known as the “representative concentration pathways” (RCP), to account for the consequences of climate policy. The same mitigation target RCP2.6 (i.e. 2.6 W/m² in 2100), is assumed for each scenarios, in line with Paris agreements to keep the increase of global mean temperature under 2°C by 2100 [40]. The background database is updated thanks to the Python library *premise* [41], following the Integrated Assessment Models (IAMs) scenario SSP1-RCP2.6 (REMIND), SSP2-RCP2.6 (IMAGE) and SSP5-RCP2.6 (REMIND). The prospective values of the SoSOS are updated according to the assumptions of these scenarios regarding the population and the future costs, as depicted in Table 1. Specific data on the electrification of the French passenger car fleet and price trends come directly from the French Réseau de Transport d'Electricité (RTE): the number

of electric cars will reach in France, 8 million in 2030 and 38.4 million in 2050, representing then 93.4% of the total passenger car fleet. [42], [43]. The final score, known as the 'Relative impacts assigned to the SOS', is obtained by dividing the LCA score by the corresponding SoSOC. If the result is equal to one or less than one, then the upscaling of the studied battery design will not exceed the considered PB and could be considered as sustainable for this impact category. An uncertainty zone is also taken into account, related to the upper limit of PB for climate change that is equal to 450ppm CO₂ (compared to the reference value 350 ppm) [1], [11].

Table 1. Share of Safe Operating Space for the Climate Change (CC) for the electric automotive battery sector in France with three sharing principles and three prospective scenarios

Scenarios	Year	$SoSOS_{CC}^{statu\ quo}$	$SoSOS_{CC}^{FCE\ only}$	$SoSOS_{CC}^{FRCap+FCE}$
		kg CO ₂ eq/year	kg CO ₂ eq/year	kg CO ₂ eq/year
Reference	2020	5.24e7	4.89e7	2.05e7
	2030	1.03e9	6.69e8	2.60e8
SSP1- RCP26	2050	4.61e9	3.08e9	1.10e9
	2030	1.06e9	6.69e8	2.68e8
SSP2-RCP26	2050	5.09e9	3.08e9	1.16e9
	2030	1.03e9	6.69e8	2.61e8
SSP5- RCP26	2050	4.79e9	3.08e9	1.15e9

3. Results

3.1. Relating LCA scores to the several SoSOS

Figure 1 shows the relative impacts to the PB for CC of the studied battery, for different sharing principles and prospective scenarios. The green zone below one means the impact score is inferior to the PB, while the red zone indicates the PB is exceeded and the orange zone refers to the uncertainty area. The first column gathers the results for the reference year 2020 for the three different sharing principles, while the next columns show the results in 2030 and in 2050 and are subdivided for each SSP scenarios.

It can be noticed on Figure 1 that the electrification of the French car fleet with this battery design exceeds the assigned $SoSOS_{CC}$ in every case. Relative impacts range from two to over nineteen, meaning this battery design exceeds the PB for CC by two to nineteen times.

The results with the sharing principle *statu quo* leads to the smallest results, giving a high $SoSOS_{CC}^{statu\ quo}$ as depicted in Table 1. Concerning the two other sharing principles, the expenditure for batteries in French households is comparatively small when compared to the global expenditure, which results in a smaller $SoSOS_{CC}$ and therefore, higher relative impacts. The gap between the *FCE only* and the *FRCap+FCE* outcomes might be attributed to the fact that the annual expenditure of a French resident is higher than the global average. On the other hand, the choice of SSP also leads to a noticeable discrepancy, mainly due to the carbon intensity of the electricity mix that is very different depending on the decarbonization pathway.

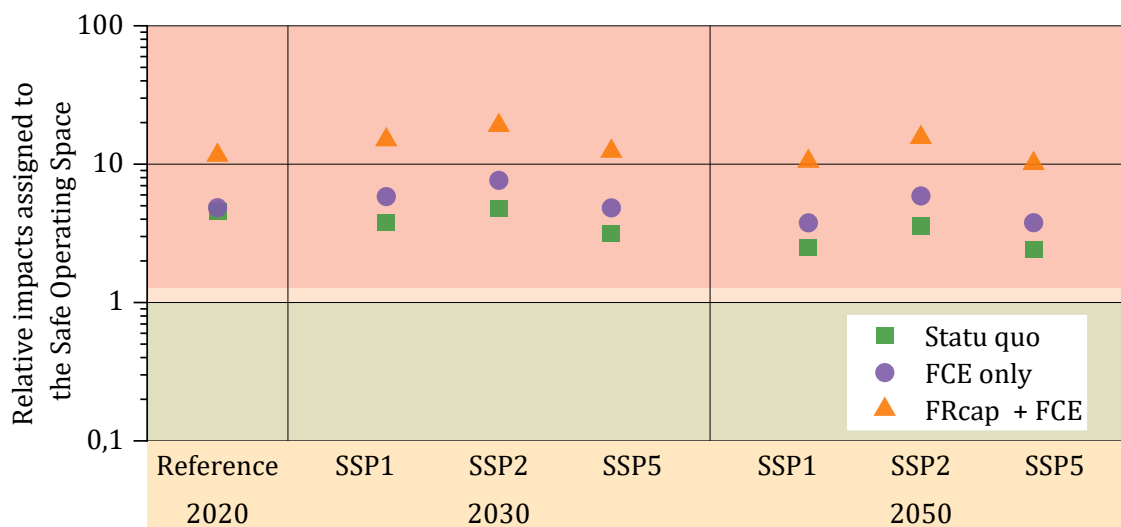


Fig. 1. Relative impacts in regards of the PB in the Climate Change, for the upscaling of a 33kWh NMC battery for the electrification of the French private car fleet, for several sharing principle for the reference year, and for prospective scenarios

Indeed, Table 2 shows very different evolution of the carbon intensity of electricity in China and in France depending on the chosen SSP (and the associated background database). Since the electricity production is one the most contributor to the GWP of the battery [28], [44], [45], those differences in the carbon intensity could partly explain the influence of the SSP choice on relative score.

Table 2. Global Warming Potential of the electricity production (medium voltage) in China and in France depending on the SSP and the year

Scenarios	Year	'market group for electricity, medium voltage', China	'market for electricity, medium voltage', France
		GWP [kg CO ₂ eq/kWh]	GWP [kg CO ₂ eq/kWh]
Reference	2020	1.06	0.080
SSP1-RCP26	2030	0.62	0.11
SSP2-RCP26	2050	0.03	0.021
SSP2-RCP26	2030	1.04	0.21
SSP2-RCP26	2050	0.16	0.22
SSP5-RCP26	2030	0.33	0.068
SSP5-RCP26	2050	0.02	0.015

3.2. Sensitivity to the battery sizing

As suggested in the Section 3.1., these results are specific to the studied battery design. To evaluate the influence of the design parameters, the battery sizing is explored by analyzing seven sizes, by adding or removing cells from the reference 33kWh battery, increasing or decreasing thus, its total capacity. The battery sizes explored range from 25 kWh to 83 kWh. The Life Cycle Inventory and the battery lifespan are updated before computing the results. Indeed, oversizing batteries affect the cell current and thus, influence the battery ageing and its lifespan. Results for the scenario SSP2-RCP2.6 in Figure 2 demonstrate the crucial influence of the battery size on the AESA score in the Climate Change category: undersizing or oversizing largely change the relative impacts assigned the Climate Change PB for any sharing principles as early as 2030. The bigger the battery,

the higher the consumption and the higher the environmental impacts, even if the lifespan might increase although. On the other hand, a too small battery will not be able to perform the usage profile over many years, resulting in shorter lifetime and higher impact score. This aspect will be further detailed in another article.

This sensitivity analysis highlights the opportunity that offers this method to evaluate the AESA score of any battery design regarding several decarbonization pathways and could be used as an ecodesign tool for battery system designers.

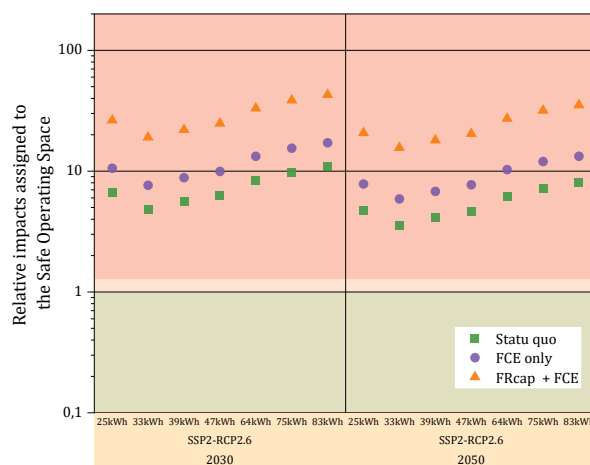


Fig. 2. Relative impacts in regards of the PB in the Climate Change, for the electrification of the French private car fleet, depending on the battery, with several sharing principle for the reference year, and for the SSP2-RCP2.6 IAM scenario

4. Discussion

Assessing the absolute sustainability of a given design is a challenging objective that requires addressing several issues. First, only the Climate Change Planetary Boundary is addressed in this study, but of course, the other boundaries must be addressed to conclude on the absolute sustainability of this battery design. The SoSOS should be updated for each

impact category for that purpose.

Moreover, the choice of the sharing principle has been highlighted in this paper as the most sensitive parameter, in line with the literature [6], [9], [12]–[15]. Therefore, there is a critical need to explore new ways of computing SoSOS and to identify best practices and guidelines for selecting an appropriate SoSOS depending on the sector under study. This would facilitate a more thorough comprehension of the benefits and limitations of each sharing principle and enable the creation of guidelines to select the appropriate one(s) for the respective product or service.

The same is true for the choice of the prospective scenarios, which has a decisive influence on the final results. Looking into the future enables a better understanding of how the environmental impact of the common design may evolve and determine if it necessitates a more eco-designed battery as highlighted in [8]. Therefore, it would be interesting to re-analyze our results with other IAM scenarios, such as SSP3 and SSP4 that are more pessimistic on the decarbonization path, but also with different mitigation targets to explore a wider range of possibilities. New visions of the future should also be explored using scenarios that depict a society with decreasing reliance on technology, promoting simplicity, low-tech and sobriety.

To accurately depict the influence of the changes in electricity production throughout the battery's lifespan, the electricity mix should be updated annually for each scenario and, accordingly, the battery recharge impacts should be recalculated as well. Such an undertaking requires a more sophisticated structure that can be accomplished through a dynamic LCA.

At last, performing a LCA-based AESA requires extensive information to construct the LCI, but also to construct the PB framework. This information is transdisciplinary and encompasses various fields, ranging from engineering to economics. This could pose challenges in finding reliable and accurate data. Consequently, arbitrary assumptions must be made, leading to potentially uncertain outcomes. This should be considered when interpreting AESA results, and additional research is necessary to enhance this framework and establish guidelines for the harmonization of methodologies.

5. Conclusion

The Planetary Boundary framework has been adapted here to assess the Absolute Environmental Sustainability (AESA) to the electric automotive battery sector in the context of the electrification of the French private car fleet. The PB for Climate Change has been downscaled with three different sharing principles, based on several distributive justice theories. A prospective LCA-based AESA has been performed on a real commercial battery under numerous prospective scenarios to explore three decarbonization pathways and recompute the final scores with the updated background databases. The results indicate that, presently and in the future, this battery design surpasses the Planetary Boundary for Climate Change, which highly suggests to ecodesign battery to make possible the sustainable upscaling of automotive batteries. A significant sensitivity to the

sharing principles has also been identified, along with prospective socioeconomic pathways.

The methodology's potential to adapt to different battery designs has been demonstrated using the example of oversized and undersized batteries. Therefore, this methodology could be a decision metric to assess the absolute sustainability of the upscaling of one battery design in a prospective perspective.

Appendix A. Principles for computing the Share of Safe Operating Space for the battery sector in France

Table 1. Equations used for each sharing principles

Sharing principles	Equation
Statu quo	$\alpha_{statu\ quo}^{CC} = Pop_{FR} \times \frac{I_{car}^{CC}}{I_{GLO}^{CC}} \times \frac{n_{EV}}{n_{car}} \times \frac{I_{battery}^{CC}}{I_{EV}^{CC}}$
FCE only	$\alpha_{FCE}^{CC} = \frac{FCE_{vehicle}}{FCE_{GLO}} \times \frac{CAPEX_{battery}}{CAPEX_{EV}} \times \frac{n_{EV}}{n_{car}}$
FRcap + FCE	$\alpha_{FRcap-FCE}^{CC} = \frac{Pop_{FR}}{Pop_{GLO}} \times \frac{FCE_{vehicle}}{FCE_{FR}} \times \frac{CAPEX_{battery}}{CAPEX_{EV}} \times \frac{n_{EV}}{n_{car}}$

With $\alpha_{statu\ quo}^{CC}$ the share of the PB for CC allocated according to the chosen sharing principle, I_{car}^{CC} the annual carbon footprint of a French inhabitant for his/her personal car, I_{GLO}^{CC} the global GHG emissions, I_{EV}^{CC} / $I_{battery}^{CC}$ is the contribution of the battery to the total impact on climate change of an EV, n_{EV} and n_{car} are respectively the number of electric vehicles and the total number of individual French vehicles, FCE the final consumption expenditure, Pop the population of one specific area, $CAPEX$ the capital expenditure.

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