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Environmental evaluation of future generations of batteries, implementation of eco-design in a R&D context

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Abstract. Rechargeable batteries play a decisive role in the deployment of low-carbon electric mobility. However, their environmental cost in terms of resource depletion, toxicity, and end-of-life recovery, among others, must not be overlooked. Because of the massive volume of batteries foreseen to be deployed worldwide and the rapid evolution of the battery industry with the emergence of new high-density energy technologies, it is necessary to analyse their technological feasibility according to a lifecycle approach, in order to identify the environmental impacts of these innovations when they are at a low level of maturity. The objective is to integrate environmental performance criteria early in the development of these new generations of batteries. This work aimed at supporting the actors involved in the technological research to incorporate the environmental dimension into their R&D activities. Thus, two technologies (advanced lithium-ion and lithium-sulphur) with different technological maturities were analysed through a multi-criteria environmental assessment approach. The method applied fulfils the support requirements of the upstream actors during the implementation of their R&D activities in the design of future generations of batteries for electric mobility.

1 Introduction

Electric vehicles are seen as an important means of action to achieve global climate change goals, and then, Li-ion batteries play a decisive role in the deployment of low-carbon electric mobility. That is why the planned development of electric mobility worldwide will increase the need for batteries. The International Energy Agency estimates that for 2030, this need will be multiplied by 17 [1]. In response to this need, the battery industry is evolving rapidly with the emergence of new high-density energy technologies such as new generation Li-ion with reduced cobalt and nickel content, all-solid-state battery, or Li-Sulphur accumulators, without being exhaustive.

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Because their environmental cost in terms of resource depletion, toxicity, energy consumption, end-of-life recovery, etc., is not negligible, it is necessary to analyse their technological feasibility according to a lifecycle approach, and to identify their environmental challenges. To achieve effective sustainable design of new battery generations, the integration of environmental aspects from the early stages of the design process and a multi-criteria approach to balance environmental requirements with other traditional requirements (performance, cost, safety, regulation, etc.) is essential [2-4]. Similarly, the integration of all levels of the value chain is recommended so that actors willing to work together can find ways to improve their overall sustainability [5].

Even though a large number of designers are currently seeking to integrate environmental performance from the early stages of the design project, the majority of methods and tools available in the literature do not consider the level of technological maturity of the products they assess. So far, few examples of eco-design methods that take into account the constraints of new technologies under development with a low Technological Readiness Level (TRL) can be found in the literature. Some of these examples are shown below.

Belchi Lorente proposes an agile product model that allows the designer to take into account the technological evolutions of high-tech products throughout the life cycle during the design phase [6]. Gazbour developed a method based on the principle of estimating the technical, economic and environmental evolution rates of the new technology through a reference database and a decision making step based on the quantitative results provided by the "ECO PV" tool [7]. Hung *et al.* advance their "Lifecycle Screening of Emerging Technologies method" (LiSET) that uses available data to systematically and transparently assess the environmental performance of technologies at low levels of maturity [8].

In order to address the need for integrating the environmental criteria into the R&D vision by appropriation of the eco-design method and it implementation in the development of more efficient and lower cost technologies, a methodological proposal, as well as an example of its application are presented below.

2 Proposed methodology

With the aim of providing an environmental perspective to the actors involved in the technological research of innovative batteries by providing a method to help them identify levers for improving environmental performance, a literature review was carried out. Since the added value of this work will be mainly attributed to the upstream stage of the R&D process, the technological research stage, the literature review focused on the methods designed and intended for the development of technologies with a low level of maturity.

Bergerson *et al.* through a review of 19 research articles, discuss the research needs related to the LCA of emerging technologies [9]. They summarise the achievements, challenges and opportunities across a large range of applications (novel materials, transportation, infrastructure and energy technologies, etc.). Thus, it is concluded that it is still necessary to provide structured guidelines to support researchers in obtaining data and selecting relevant assessment tools. The result of this review confirms the need for an eco-design method adapted to the technological research stage.

To meet this identified need, the proposed methodological approach is composed of three steps. The first step aims to define the “classic” eco-design process thanks to the realization of state-of-the-art studies according to the identified research fields. The second step aims to define the research department’s R&D process to map it. In order to establish the mapping, it was necessary to compare the conventional process and the current and desired eco-innovation processes in the Research and Technology Organization (RTO) with the vision of the batteries technical teams. These stages were developed in parallel to lead to the third step of integration of the environmental dimension where the objective is to incorporate the environmental dimension into the battery designers' R&D process in the RTO, to assess the environmental impact of new technologies for electric mobility over their entire life cycle, according to a LCA approach, and thus to look into eco-design alternatives.

To integrate successfully the operational environmental dimension into all R&D activities, the eco-design method to be developed must be addressed to the entire team involved in the design process. This method should also consider all the resources, needs, levers of action and limits in terms of environmental assessment throughout the value chain. Therefore, twelve individual semi-directed interviews with experts from the technical teams operating at different levels of the value chain were conducted. These exchanges made it possible to identify three moments of support adapted to three stages of technological development: Project set-up, daily R&D operations and final evaluation of the technology. Similarly, these technical teams expressed the current perceptions, importance criteria and interests of integrating the environmental dimension in R&D activities for the priority consideration of this criterion. An example of this is the need for a specific resource impact assessment of these new batteries' generations.

3 Application

In response to these requirements, a preliminary multi-criteria environmental assessment of two emerging technologies at the cell level was performed: Li-Sulphur and advanced Li-ion.

3.1 Systems description

The technologies were modelled in an industry representative prismatic PHEV2 cell format (26.5x91x148 mm hard casing). Specifications of these cells are given in Table 1.

Table 1. Cell system description and components considered in the two technologies assessed.

Technology	*Advanced Li-ion*	*Li-Sulphur*
Cell energy ***(Wh)***	245	169
Cell energy density–by volume ***(Wh/L)***	686	474
Cell energy density–by mass ***(Wh/kg)***	281	372
Cell mass ***(g)***	869	455
Positive active material	Nickel rich (NMC811)	Sulphur
Negative active material	Graphite/silicon	Lithium
TRL [10]	6-*8: qualification and technological operability*	3-6*: advanced search and technology demonstration*

3.2 Life cycle assessment (LCA)

The characteristics of the cradle-to-gate life cycle assessment are specified in Table 2. Regarding the life cycle inventory, the technical teams provided primary data used for material balance in the form of Bill of Materials. For the upstream stages of cell production Ecoinvent v.3.6 database was considered. That is why, for the raw material stage, the energy consumption is included, while for the cell production and assembly stages, only the materials are currently considered.

Table 2. LCA characteristics method.

Functional unit	1 kWh of storage capacity
Perimeter	Cradle to gate (assembly without energy)
Characterization method	EF 3.0
LCA Software	Simapro 9.1

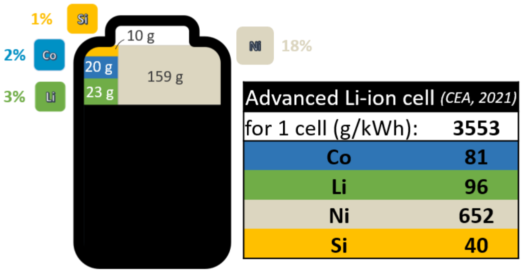
Considering the EF 3.0 characterization method, the environmental performance of these cells was assessed with the 16 indicators of the method, but only two indicators of interest are presented in this paper: Climate change and Resource use, minerals and metals. The results for these two indicators are shown in Table 3.

Table 3. LCA results for Climate change and Resource use, minerals and metals' indicators.

Battery cell technology	**Climate change** (kg CO_2 eq/kWh battery capacity)	**Resource use, minerals and metals** (g Sb eq/kWh battery capacity)
Advanced Li-ion	70	1.4
Li-Sulphur	21	0.4

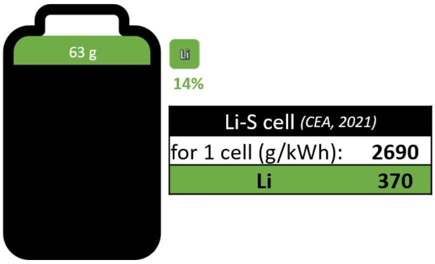
3.3 Resources' impact assessment

To carry out the study of the impact on material resources, the European Union definition of criticality was considered, which defines the CRMs (Critical Raw Material) as the raw materials that combine a high importance to the EU economy and a high risk associated with their supply [11]. Nickel is not part of this list; however, it is considered as a critical material in the battery industry and it was therefore added in this study. Fig.1 and 2 describe the content of each of the four CRM assessed in the two technologies.



Advanced Li-ion cell *(CEA, 2021)*	
for 1 cell (g/kWh):	3553
Co	81
Li	96
Ni	652
Si	40

Fig. 2. Content of CRMs in an advanced Li-ion cell.



Li-S cell *(CEA, 2021)*	
for 1 cell (g/kWh):	2690
Li	370

Fig. 1. Content of CRMs in a Li-Sulphur cell.

4 Results and discussion

The methodology proposed aims at identifying what are the environmental challenges of new battery technologies being developed for electric mobility and what eco-design approaches should be developed and followed to support the development of low TRL batteries and to ensure that they have the least impact on the environment over their entire life cycle.

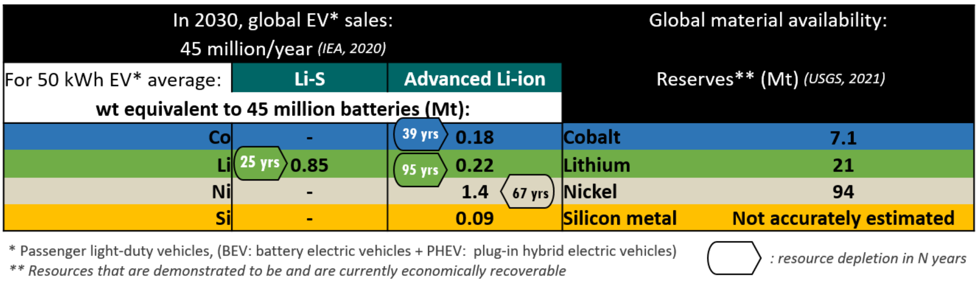
This way, the impacts of materials used in terms of kg $CO_{2\ eq}$/kWh battery capacity are 70 for the advanced Li-ion and 21 for the Li-Sulphur technology. In addition, for the Resource use, minerals and metals category, the impact of one advanced Li-ion battery cell is 1.4 g Sb_{eq}/kWh battery capacity, while the impact for Li-Sulphur technology is 0.4.

This multi-criteria environmental assessment shows that the materials that have the greatest impact on environmental performance, for these two indicators, are, in the case of the advanced Li-ion cells the electrode materials (positive and negative) and the negative current collector material; and for the Li-S cells the electrolyte materials, the cell container materials and the positive electrode materials. According to the values in grams per kWh shown in Fig.1 and 2, the advanced Li-ion technology needs a larger variety and quantity of CRMs. However, due to the lower voltage of this chemistry, Li-S technology requires on its side more lithium.

To get a better notion of the resources impact of these technologies and according to the prospects for EV deployment described in the Sustainable Development Scenario by the IEA, in 2030, global EV sales will reach 45 million vehicles per year [1]. Therefore, the quantities of CRMs required to produce 2.25 TWh of batteries per year (45 million of Li-S batteries of 50 kWh energy capacity each) are 0.85 Mt of lithium, and to produce the same capacity of NMC811 batteries 0.18 Mt of cobalt, 0.22 Mt of lithium and 1.4 Mt of nickel are needed, as shown in Table 4.

Considering, the global material availability of each CRM [12-15], the time before depletion of these reserves can be roughly estimated. In the case of Li-S technology, the lithium resources would be sufficient for 25 years, while for the second technology, the lithium resources would be sufficient for 95 years, the cobalt resources for 39 years and nickel for 67 years. Despite the fact that the reality of resource depletion is more complicated, because of reserves constant changes and issues associated with flows, these figures already give an idea to the battery technical teams of what is at stake in terms of CRM consumption.

Table 4. Resource consumption by technology according to the IEA prospects for EV deployment [1].



In 2030, global EV* sales: 45 million/year *(IEA, 2020)*			Global material availability:	
For 50 kWh EV* average:	**Li-S**	**Advanced Li-ion**	Reserves** (Mt) *(USGS, 2021)*	
wt equivalent to 45 million batteries (Mt):				
Co	**-**	**39 yrs** **0.18**	**Cobalt**	**7.1**
Li	**25 yrs** **0.85**	**95 yrs** **0.22**	**Lithium**	**21**
Ni	**-**	**1.4** **67 yrs**	**Nickel**	**94**
Si	**-**	**0.09**	**Silicon metal**	**Not accurately estimated**

* Passenger light-duty vehicles, (BEV: battery electric vehicles + PHEV: plug-in hybrid electric vehicles)
*** Resources that are demonstrated to be and are currently economically recoverable*

⬡ *: resource depletion in N years*

5 Conclusions and outlook

Assuming the same lifespan for the two technologies, which is a strong assumption, Li-S preliminary results show that the materials' choice of this cell technology has a better environmental performance with about 70% lower impacts in terms of Global Warming Potential, but on the contrary a significantly higher consumption of lithium. However, it should be remembered that in this preliminary life cycle assessment, during the production and assembly stages the energy consumption is not included. The comparative analysis of these two new technologies was made based on only two indicators that are relevant in this industrial sector: Climate change and Resource use, minerals and metals indicators. Nevertheless, by not analysing into details other types of impacts (human toxicity, eutrophication, water use, etc.) in the final assessment, there may be a risk of overlooking all environmental hotspots and possibly omitting the transfer of impacts. This will be analysed in a future work.

Within this IEA scenario, where about 35% of market sales will be attributed to EV by 2030, the theoretical reserve consumption brings out the depletion for three essential materials for these new battery technologies in a time frame of decades: lithium, cobalt and nickel. That is why, during the eco-design of these technologies, as well as encouraging the content reduction of these materials, it is necessary to consider, from a very early design stage, the end-of-life recovery issues. To increase the recovery of critical raw materials is one of the challenges that must be addressed in the move to a more circular economy.

For future work within the R&D adapted eco-design method, currently in development within the framework of a PhD research project, it will be necessary to estimate the impacts, according to a prospective vision depending on resources availability and on potential market of each technology. For this, a specific attention for end-of-life assessment (reuse, remanufacturing for second life and recyclability potentials), taking into account regulation and innovation, must be reckoned.

It will also be necessary to identify how this method can be successfully adopted within any Research Team involved in the technological development of new battery technologies.

This application could support a sustainable development of the post-lithium generations and contribute to the development of an environmentally virtuous value chain for future batteries.

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