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SOCIETAL LCA

Methodology for social life cycle impact assessment enhanced with gender aspects applied to electric vehicle Li-ion batteries

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Abstract

Purpose The objective of this study is to assess the potential social risks and benefits of EV Li-ion batteries by combining the S-LCA framework with gender aspects throughout all the life cycle phases of the battery.

Methods The social life cycle assessment (S-LCA) methodology has been applied to determine social concerns about a lithium-ion (Li-ion) battery pack design for electric vehicles (EVs) from cradle to grave. A questionnaire based on UNEP S-LCA guidelines and literature case studies of S-LCA on batteries and the energy industry has been prepared for each of the stakeholder categories and distributed among experts in the Li-ion battery sector (more than 21 industrial and academic experts representing the whole battery value chain). Furthermore, the social assessment also includes updated gender aspects to provide wider and more comprehensive social impacts to ensure a gender-neutral approach.

Results and discussion The Li-ion battery presents a positive social impact in all the stakeholder categories evaluated, where the worker category has the best social performance driven by the highest score (scores range from 0 to 1, where 0 is the worst social performance and 1 is the best) in 13 indicators out of 23. Furthermore, local community, consumers, and society categories have a good social performance attributed to the absence of involuntary resettlement of individuals, the possibility of the product being reused for other purposes and technology accessible and affordable to developing countries, among others. Four out of seven indicators to evaluate the gender aspects and impacts have the highest score, demonstrating a commitment to fostering an inclusive and equitable work environment. The end-of-life phase presents a positive social performance with a score of 0.77 out of 1 attributed to the presence of infrastructure to dispose of product components other than landfill and incineration responsibly, the possibility of the product to be reused for other purposes and clear information provided to consumers on end-of-life options, among others.

Conclusions The study presents generally good social impact and gender neutrality on the battery pack design. It gives an insight into the actual status of Li-ion battery social and gender impacts, and the results can be useful to policymakers to design and implement strategies for the welfare of various stakeholders.

Keywords Li-ion battery · Social life cycle assessment · Gender issues · End of life · Life cycle sustainability assessment · Electric mobility

1 Introduction

1.1 Environmental and social impacts

Lithium-ion (Li-ion) batteries are a critically important technology for facilitating the electrification of mobility and energy transition to move towards a more sustainable and decarbonised future. Despite the environmental and social benefits related to the use of lithium-ion batteries, there are significant impacts related to their production.

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Li-ion battery technology for EVs, indeed, is based on the use of raw materials such as lithium, cobalt, and natural graphite, which are associated with environmental impact (Thies et al. 2019). To obtain these critical raw materials, different processes and techniques such as brine evaporation, mining, or oil and gas extraction are used. In addition to these activities, mining operations and material manufacturing can expose workers and the local environment to toxic chemicals, unregulated effluents, and pollution, potentially leading to serious health and posing a severe threat to the well-being of the surrounding communities and ecosystem organisms (Manthiram and Venkat 2021). Notably, cobalt mines are also home to large amounts of uranium, making these regions high in radioactivity levels (Aphra Murray 2022; Malcolm Earnshaw-Osler 2023).

Metals, minerals, and natural materials are basic to produce a broad range of goods and applications used in everyday life and modern technologies. Those raw materials that are most important economically and have high economic importance and high supply risk are called critical raw materials (European Commission 2020). For a 23.5 kWh NMC111 battery pack, NCM111 powder accounts for 25.16% of the total weight of the battery. The other materials most present in the battery cells are aluminium for the current collector, cell and module housing, and copper for the current collector and graphite, with 23.85%, 11.7%, and 14.05% of the total weight, respectively (Dai et al. 2019; Melin 2019). The cradle-to-gate LCA of this battery shows that the NMC111 powder is the most significant contributor to energy and environmental burden with 409.33 MJ/kWh and 28.49 kg CO_2 eq./kWh, accounting for 36.4% of the total energy use and 39.1% of the GHG emissions. Aluminium is also a substantial contributor with 203.38 MJ/kWh and 12.39 kg CO_2 eq./kWh, accounting for 18.1% of the total energy use and 17% of the GHG emissions (Dai et al. 2019). Aside from these contributors, graphite is a source of NO_x, SO_x, and PM10 emissions due to sulphur, nitrogen, and ash impurities burn off during the carbonation process for its production; copper accounts for SO_x emissions during the processing and refining of copper sulphide ores (Dai et al. 2019).

Along with the environmental impact, battery materials and components can have a social impact on the communities involved in the production. For example, 71% of cobalt production is mined in the Democratic Republic of Congo (DRC) (Mayyas et al. 2023; Thies et al. 2019), where child labour and dangerous working conditions are present. According to a report by the Amnesty International, tens of thousands of children in the DRC work as artisanal miners (i.e. mining by hand) for 10 to 12 h without basic protective equipment and carrying heavy loads (Amnesty International 2016). Moreover, children have been seen working in the open area under unbearable climate conditions and even being beaten by security guards (Amnesty International 2016). Therefore, it is crucial to take extreme care in developing environmentally and socially responsible technologies.

In addition to the sustainability challenge of raw material extraction, further questions are raised with the impressive growth experimented in the last years of Li-ion battery demand. Indeed, the demand stood at approximately 330 GWh, and it increased by about 65% to reach 550 GWh in 2022 (International Energy Agency (IEA) 2023a), and it is expected to reach 680 GWh and 1.525 GWh in 2025 and 2030, respectively (Lai et al. 2022). Consequently, it will lead to a large number of batteries reaching end-of-life (EoL), causing an ever-increasing battery waste that needs to be managed accordingly (Mrozik et al. 2021). Li-ion battery disposal was estimated to be 10,700 tons in 2012 and has increased progressively each year, with an estimate of up to 250,000 tons in 2020, 46,400 tons in 2025, and by 2040 could be as much as 8 million tons (Baum et al. 2022; Dobó et al. 2023). An improper or careless processing and disposal of spent batteries leads to contamination of the soil, water, and air (Mrozik et al. 2021), while their use in second-life application and material recycle represents an indispensable answer to the sustainability requirement. Currently, different types of batteries end up in landfills or are incinerated, due to the lack of adequate standards, enforcement of, inefficient, or absence of, national battery collection and recycling schemes and regulatory controls (Mrozik et al. 2021). In this frame in July 2023, the European Union sets collection, recovery, and mandatory minimum levels of recycled content targets to apply to the batteries market from stationary to mobility use (European Council 2023).

1.2 Methodology for the evaluation of the social aspects: S-LCA

Nowadays, environmental life cycle assessment (LCA) is a well-known tool used to evaluate the environmental impacts of a product or service throughout its life, from raw material extractions, transportation, manufacturing, and use of the product to end-of-life stages. Based on ISO 14040 and 14044, this methodology can be expanded into other areas, commonly known as pillars: economic aspects (life cycle costing, LCC) and social impacts (social life cycle assessment, S-LCA) (Aranda et al. 2021).

S-LCA is a methodology that assess the social and socio-economic impacts of products and services across their life cycle (UNEP 2020). S-LCA includes four phases: goal and scope, social life cycle inventory (S-LCI), social life cycle impact assessment (S-LCIA), and interpretation (UNEP 2020).

To promote the implementation of social life cycle impact assessment, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) developed "Guidelines for Social Life

Cycle Assessment of Products". The guidelines for S-LCA published by UNEP provide a baseline framework to conduct S-LCA studies, introducing six different stakeholder categories (workers, local community, society, consumers, value chain actors, and children). Each stakeholder category corresponds to one or a group of persons that are involved in the product system value chain or susceptible to being affected by its related activities throughout all life cycle stages (Bouillass et al. 2021). In support of the guidelines, the Methodological Sheets published in 2020 describe 40 social impact subcategories to evaluate potential social and socio-economic impacts. Impact categories are social and socio-economic items or attributes that describe how each stakeholder category can be affected by the potential social and socio-economic impacts of the product system. These impact subcategories are evaluated through several inventory indicators for which quantitative, semi-quantitative, and qualitative data are collected (Bouillass et al. 2021).

1.3 State of the art and introduction to the problem related to gender issues

In parallel, gender equality and inclusion have emerged as critical factors to complement a truly sustainable and equitable society. Low take-up of STEM (science, technology, engineering, and mathematics) subjects among women leads to a low percentage of women participating in technology development, reaching only 15% on average across all countries and all technology domains (Organisation of Economic Cooperation and Development (OECD) 2021). The reasons for this vary from gender stereotyping in childhood and youth (which affects choices of study and causes self-selection among female students) to social norms, and inherent gender biases in the academic community (Organisation of Economic Cooperation and Development (OECD) 2021). The gender gap in science-related careers can also be enhanced by other factors, such as women's household and caring responsibilities that reduce the amount of time dedicated to their careers, or biased performance evaluation which is often influenced by gender stereotypes about women's abilities in STEM, as well as the lack of women in high-ranking positions (Organisation of Economic Cooperation and Development (OECD) 2021). Studies (Hunt et al. 2015) show that projects with diversity or even women-only groups perform better and have a higher impact from a technological point of view than those in which only men are involved. For instance, having diversity management helps talent recruitment, to strengthen customer orientation, increases employee satisfaction, improves decision-making, and enhances the company's image (Hunt et al. 2015; Organisation of Economic Cooperation and Development (OECD) 2021).

The recognition of diverse perspectives and the integration of gender aspects in product design and development are vital for creating products that cater to the needs and preferences of all individuals. In this vein, there are different approaches and initiatives across the energy field to integrate and promote gender aspects. For instance, the International Energy Agency has a Users Technology Collaboration Programme aiming to apply gender perspectives to support the participating countries in their work to design a more efficient an

d inclusive energy system. As a result, they have created a Gender & Energy Task where with researchers' help from fields of gender and energy, analyse energy policy and technologies from gender perspectives, and provide recommendations for policy design and implementation (International Energy Agency (IEA 2023b). On the other hand, the objective of the United Nations Industrial Development Organization (UNIDO) is to promote and accelerate inclusive and sustainable industrial development. In this context, UNIDO recognizes that gender equality and the empowerment of women have significant positive impacts and consider gender mainstreaming as a key strategy (Tas et al. 2014). As a result, the organization has created a guide to mainstream gender throughout sustainable energy projects. Gender mainstreaming consists in analysing the needs, priorities, roles, and experiences of women and men as well as the integration of specific actions to address any gender-based inequalities found with the analysis (Tas et al. 2014).

The energy sector, like other STEM fields, has a lack of women employees, especially in leadership positions. Even though there are no data on the number of women in energy storage, only 22% of the EU energy sector workforce and 35% of the European workforce in the renewable energy sector are women (Hernández and Navarro-Suárez 2022). This trend persists in the lithium mining sector, where of the 24 European companies with lithium projects, the average female representation on board members is 26%, surpassing the global average of 13% (Benchmark Mineral Intelligence 2024).

The situation becomes even more complex in the realm of EVs. Despite women's heightened concern for climate change, their participation in the EV industry, both as employees and consumers, is disproportionately low (Davis 2023). Specific data on women in the EV workforce is lacking, with available information often focusing on women's roles as consumers. A 2022 survey revealed that only 29% of American women intend to purchase a fully electric or plug-in hybrid vehicle, trailing behind the 41% of men with similar intentions. This consumer trend is reflected in national vehicle registration data, where women account for 41.2% of total new vehicle registrations but only 28% of new EV registrations (Davis 2023). The evident gap both in the EV and Li-ion battery industry, particularly in leadership positions and consumer choices, needs addressing to foster innovation and ensure a diverse and equitable workforce.

1.4 Literature review

Over the last years, a considerable number of life cycle studies on EV batteries have been published, usually focused on the environmental and/or economic aspects. In contrast, the number of studies focused on the social assessment of the life cycle of Li-ion batteries is extremely low. Shi et al. (2023) combines social risk assessment and material supply concentration to compare the social sustainability of lithium-ion phosphate (LFP) battery production in China, Japan, and South Korea. However, the study mainly focused on the supply sources of the critical raw materials without considering manufacturing, use, or end-of-life phase and uses secondary data obtained from the social hotspots database (SHDB). Along similar lines, Thies et al. (2019) carry out a S-LCA to analyse the social hotspots in the supply chain of Li-ion batteries, whereas in this case, the manufacturing of the battery pack is considered to perform the analysis. Nevertheless, it only uses four social risk indicators (i.e. child labour, corruption, occupational toxics and hazards, and poverty) excluding others that could give more insight view of the social impact. Wang et al. (2019) assess indirectly the social impact of EV batteries by performing a life cycle sustainability assessment (LCSA) of EVs from raw material extractions to recycling. The data collection for the S-LCA is obtained through questionnaires and on-site interviews with stakeholders in the phases of manufacturing, operation, and recycling of the vehicle. The methodology used in this study is like the one being referred to; however, it covers fewer indicators and does not integrate gender aspects. Another study, a little bit different from the ones mentioned in the sense that it does not apply the S-LCA methodology, is the one by Hannan et al. (2021). It analyses the impact of battery energy storage systems (BESS) on achieving the UN sustainable development goals (SDGs). The assessment is done by performing literature research on the interlinkage mapping of SDGs and BESS.

Focusing on the social assessment of the end-of-life of the batteries, as aforementioned, Wang et al. (2019) conducted a cradle-to-grave analysis collecting primary data through questionnaires and on-site interviews of the stakeholders involved in the three phases of manufacturing, operation, and recycling of the vehicles, but unfortunately, no impact indicator included in the study is directly connected with the end-of-life phase. Popien et al. (2022) proposed a different approach for the end-of-life social sustainability study. They focused on the environmental, economic, and social impacts of three different recycling vehicle battery networks that vary in size and number of recycling sites in Germany (Popien et al. 2022). The social assessment was conducted with the use of secondary data provided by the Social Hotspot Database (SHDB) and the use of the following risk categories: risk of child labour (RoCL), risk of forced labour (RoFL), risk of poverty (RoP), and risk of corruption (RoC).

The literature review shows that further research is needed to conduct a comprehensive analysis of the social impact on the complete Li-ion battery's life cycle, including the raw material extraction, manufacturing, use, and end-of-life. Therefore, this paper aims to assess the potential social risks and benefits of EV Li-ion batteries by combining the S-LCA framework with gender aspects throughout all the life cycle phases of the battery. The main contributions are summarised as follows:

- The basic S-LCA framework and procedures are combined with gender aspects to ensure a neutral gender approach when designing Li-ion battery packs for EVs.
- The cradle-to-grave S-LCA of Li-ion battery (i.e. raw material extraction, manufacturing, use, and end-of-life) is performed using a total of 56 impact indicators with a special focus on the end-of-life phase.
- The S-LCA study is done with primary data obtained through a questionnaire distributed among experts in the Li-ion battery sector.

The paper is structured as follows: Sect. 2 explains the S-LCA methodology, including the definition of the goal, scope, and system boundaries, as well as the social life cycle inventory and impact assessment. Section 3 presents and discusses the results, while Sect. 4 provides key conclusions and outlines future actions.

2 Methodology

The method of S-LCA currently does not have a standardised approach or established code of practice (Chen and Holden 2017; García-Sánchez and Güereca 2019). However, frameworks such as the UNEP/SETAC S-LCA Guidelines (UNEP Life Cycle Initiative and Social LC Alliance 2020) and different literature case studies applying the life cycle approach are tools to guide the implementation of social impact assessment that we have followed.

Figure 1 shows the six steps followed to perform the S-LCA. In steps 1 and 2, UNEP S-LCA and United Nations

Fig. 1 Main steps to perform the S-LCA

Industrial Development Organisation (UNIDO) guidelines as well as literature case studies of S-LCA on batteries and energy industry are used as basis in step 3 for the definition and selection of impact indicators for an integrated gender social assessment. In steps 4 and 5, a questionnaire based on the impact indicators selected in step 3 has been prepared and distributed among more than 21 industrial and academic experts in the Li-ion battery sector that participate in the ALBATROSS project (ALBATROSS H2020 2021). Step 6 consists of implementing the S-LCA framework, which entails four phases (goal and scope definition, social life cycle inventory (S-LCI), social life cycle assessment (S-LCA), and interpretation) and is presented in the next sections.

The S-LCA framework follows similar steps or phases to Life Cycle Analysis ISO 14040:2006 as described in Table 1.

2.1 Goal, scope, and system boundaries

The goal of this S-LCA is to evaluate the social impacts of a battery pack design and evaluate the gender aspects to ensure a neutral gender approach. The health aspects are addressed from the S-LCA impact categories related to health and safety and health living conditions (see the indicators in Table 3).

ALBATROSS addresses the needs of electric and hybrid electric passenger vehicle market by overcoming driver concerns relating to battery range and anxiety, cost, long-term reliability, and excessive charging times. ALBATROSS will develop, using a BMW i3 passenger vehicle as a baseline, an integrated approach of smart batteries combined with lightweight designs to achieve peak energy density > 200 Wh/kg, increase driving range to 480 km, and reduce charging times by 25%.

The ALBATROSS project participants, as manufacturers, developers, and producers, have a comprehensive understanding of the EV battery value chain. Therefore, to align with the project's objective, the scope of this study has been defined from cradle to grave. This approach ensures that the study results encompass social concerns related to manufacturing, use, and end-of-life stages, including reuse and recycling.

The S-LCA guidelines propose to define a functional unit in the goal and scope phase. However, there has been a lot of discussion about whether a functional unit should be used. Osorio-Tejada et al. (2020) discusses that it could be more appropriate to perform an S-LCA through an organization perspective, especially when social impacts are shaped by an organization's acts toward stakeholders rather than physical flows. Nevertheless, establishing a functional unit for comparing product systems on an equal basis in S-LCA is not feasible. Unlike traditional LCA, which focuses on the function delivered by a product, S-LCA measures the socioeconomic impacts related to a company's behaviour (Bonilla-Alicea and Fu 2022; Singh and Gupta 2018; Tsalidis 2020; Wu et al. 2014).

Furthermore, S-LCA works with information about the characteristics of products and processes and/or their own companies, which are not relevant to express per unit of process output (Benoît et al. 2010). The challenge of relating social aspects to the functional unit induces conducting an organizational analysis (Osorio-Tejada et al. 2020).

A company-based approach has been used in this study, considering the different organizations involved in the product's value chain. As a result, the findings are not presented based on a functional unit. Our intention in emphasizing the distinction between product and company S-LCA is to underscore that S-LCA goes beyond the functional aspects of a product and delves into the broader societal implications of a company's behaviours. By focusing on the company level, S-LCA allows to capture and analyse the multifaceted impacts of corporate actions on society, encompassing issues like labour practices, community relations, and ethical considerations.

The identification and selection of stakeholder categories and subcategories, defined by the UNEP/SETAC Methodological Sheets (UNEP 2021), were based on criteria of relevance to the study's goal and scope. Several criteria are considered to ensure the inclusion of relevant stakeholders with significant impacts. First and foremost, stakeholder categories are chosen based on their direct involvement in

Table 1 ISO 14040:2006 framework and implementation for a S-LCA

Phase	ISO 14040:2006 implementation in the study
1. Goal and scope definition	Defines the aim of the study, the product system to be studied, and sets the boundaries and assumptions. It also identifies the stakeholders and social aspects to be assessed.
2. Inventory analysis	Involves collecting data on social conditions from experts participants involved in the ALBATROSS project across the product's life cycle through a questionnaire, focusing on stakeholder categories identified in phase 1.
3. Impact assessment	Assesses the data collected in phase 2 to understand social impacts on stakeholders. This includes categorising, aggregating, and evaluating data to reflect social performance.
4. Interpretation	Analyses results to make informed decisions and recommendations, identify significant issues, and provide a clear understanding of the S-LCA findings.

Table 2 Stakeholder category and subcategory identification

Stakeholder category	Subcategory
Worker	Child labour Fair salary Forced labour Hours of work Equal opportunities/discrimination Health and Safety Social benefit/social security Sexual harassment
Local community	Local employment Access to material resources Safe and healthy living conditions Delocalization and migration
Society	Public commitment to sustainability issues Contribution to economic development Technology development
Consumers	Health and safety Transparency End-of-life responsibility Feedback mechanism
Value chain actors	Promoting social responsibility

or impact of the life cycle of Li-ion batteries. Additionally, consideration is given to ensure comprehensive coverage of the entire value chain, from raw material extraction to end-of-life treatment. Moreover, stakeholders are prioritised based on the significance of their potential social impacts, including issues such as human rights, labour condition, and community health and safety. Representation of diverse stakeholder interest and perspectives is ensured, encompassing industry, academia, consumers, affected communities, and other relevant groups. Finally, the accessibility of information plays a crucial role, with stakeholders selected based on the availability and accessibility of relevant data and information needed for the S-LCA. The details are displayed in Table 2. There is a sixth stakeholder category called children, which encompasses education provided in the local community, health issues for children as consumers, and children's concerns regarding marketing practices. However, the authors of this paper have decided to exclude it as it has been deemed irrelevant to the analysis of the battery pack design.

2.2 Social life cycle inventory (S-LCI)

The social inventory also involves the selection of indicators associated with the subcategories used in the social impact assessment, as well as the data collection to measure them in a quantitative, semi-quantitative, or qualitative way.

For the selection of the impact indicators, we have used UNEP/SETAC Methodological Sheets (UNEP 2021) as well as literature to select relevant indicators based on the goal and scope of the study. Table 3 summarizes the indicators used in the analysis. The desired direction is the expected answer with 0 negative impact or as low as possible. For example, in the indicator "equal wages for doing the same task", the expected answer is yes. The desired direction or answer is taken into consideration in the interpretation of the results and as a reference to determine what is a positive or negative social impact. For example, in the indicator "percentage of child labour", the desired direction is negative because we want it to be 0 or as low as possible.

In this vein, foreground data is collected by a questionnaire sent to all the expert participants involved in the ALBATROSS project (ALBATROSS H2020 2021). The data inventory is composed of 57 indicators categorized by stakeholder and type of question (quantitative, semi-quantitative, and qualitative). We introduced eight indicators in the impact category of equal opportunities/discrimination to analyse the gender impact. The selection of these indicators is based on literature review of gender equality in general and specifically in the energy sector.

2.3 Social life cycle impact assessment (S-LCIA)

According to the S-LCA guidelines, the impact assessment stages consist of establishing a relationship between inventory data, the impact categories (classification), and the impact subcategories. Afterwards, a characterization model is used to assess the results. So far, no consistent or specific impact assessment method has been proposed in the guidelines or case studies (García-Sánchez and Güereca 2019; Wang et al. 2016).

There are two impact assessment approaches: type I called reference scale social impact assessment (RS S-LCIA) and type II called impact pathway social impact assessment (IP S-LCIA). Type I uses established nominal reference values called performance reference point (PRP) to assess the past or current social performance or social risk related to the behaviour of the organization involved in the product along its life cycle (Bouillass et al. 2021). The indicators are aggregated following a scoring system and the inventory values are compared to the PRP to determine the social impacts, and whether the impacts are positive or negative (Bonilla-Alicea and Fu 2019; Parent et al. 2010). Type II assesses the consequences resulting from the product system by establishing a cause-effect relationship between the input inventory data and the midpoint and endpoint level impacts (Bouillass et al. 2021). The problem with type II is that "cause-effect relationships are not simple enough or not known with enough precision to allow quantitative cause-effect modelling" (Lobsiger-Kägi et al. 2018). Moreover, it can only be used to assess the social impacts for a single stakeholder, the workers, and for a very restricted number of impact subcategories (Bouillass et al. 2021). Choosing type I or II depends on the purpose of the study: type I is used to

Table 3 Indicator summary

#	Indicator name	Impact category	Desired direction/answer	Indicator type
Worker				
1	Percentage of child labour	Child labour	Negative	Quantitative
2	Percentage of children working by country and sector	Child labour	Negative	Quantitative
3	Lowest-paid worker, compared to the minimum wage	Fair salary	Yes	Semi-quantitative (Yes/No)
4	Living wages by country	Fair salary	Positive	Quantitative
5	Minimum wage by country	Fair salary	Positive	Quantitative
6	Number of hours effectively worked by female employees	Working hours	Positive	Quantitative
7	Number of hours effectively worked by male employees	Working hours	Positive	Quantitative
8	Possibility of flexible work	Working hours	Yes	Semi-quantitative (yes/no)
9	Freedom of workers to end their employment	Forced labour	Yes	Semi-quantitative (yes/no)
10	Percentage of forced labour by region	Forced labour	Negative	Quantitative
11	Presence of gender non-discrimination-policy	Equal opportunities/discrimination	Yes	Semi-quantitative (yes/no)
12	Presence of the gender committee	Equal opportunities/discrimination	Yes	Semi-quantitative (yes/no)
13	Presence of recruitment policies targeting women	Equal opportunities/discrimination	Yes	Semi-quantitative (yes/no)
14	Presence of maternity leave policies	Equal opportunities/discrimination	Yes	Semi-quantitative (yes/no)
15	Presence of paternity leave policies	Equal opportunities/discrimination	Yes	Semi-quantitative (yes/no)
16	Equal wages for doing the same task	Equal opportunities/discrimination	Yes	Semi-quantitative (yes/no)
17	Women in the labour force participation rate by country	Equal opportunities/discrimination	Positive	Quantitative
18	Country gender index rating	Equal opportunities/discrimination	Positive	Quantitative
19	The potential of technology to affect the health and safety of workers during the manufacturing phase	Health and safety	1	Semi-quantitative (1–5 scale)
20	The potential of technology to affect the health and safety of workers during the end-of-life phase	Health and safety	1	Semi-quantitative (1–5 scale)
21	Appropriate safety education and training provided to employees	Health and safety	Yes	Semi-quantitative (yes/no)
22	Occupational accident rate by country	Health and safety	Negative	Quantitative
23	Number/percentage of injuries or fatal accidents in the organization by job qualification	Health and safety	Negative	Quantitative
24	Appropriate protective gear required in all applicable situations	Health and safety	Yes	Semi-quantitative (yes/no)
25	Social benefits provided to workers (e.g. health insurance, pension fund, childcare, education, and accommodation)	Health and safety	Positive	Qualitative
26	Percentage of permanent workers receiving paid time off	Social benefit/social security	Positive	Quantitative
27	Number of sexual harassment incidents	Sexual harassment	Negative	Quantitative
28	Efforts by the organization to reduce the risk of sexual harassment	Sexual harassment	Yes	Semi-quantitative (yes/no)
Local community				
29	Presence of a certified environmental management system	Access to material resources	Yes	Semi-quantitative (yes/no)
30	Levels of industrial waater use	Access to material resources	Negative	Quantitative
31	Extraction of material resources	Access to material resources	Negative	Quantitative

Table 3 (continued)

#	Indicator name	Impact category	Desired direction/answer	Indicator type
32	Individuals who resettle (voluntary or involuntary) that can be attributed to the organization	Delocalization and migration	1	Semi-quantitative (1–5 scale)
33	Management efforts to minimize the use of hazardous substances	Safe and healthy living conditions	Yes	Semi-quantitative (yes/no)
34	Exposure of the local community to injuries, harm, and contagious diseases as a result of the company's activity	Safe and healthy living conditions	1	Semi-quantitative (1–5 scale)
35	Pollution levels by country	Safe and healthy living conditions	Negative	Quantitative
36	Percentage of the workforce hired locally	Local employment	Positive	Quantitative
37	Strength of policies on local hiring preferences	Local employment	Yes	Semi-quantitative (yes/no)
38	Number of local jobs created about final product unit	Local employment	Positive	Quantitative
39	Percentage of spending on locally-based suppliers	Local employment	Positive	Quantitative
40	Unemployment statistics by country	Local employment	Negative	Quantitative
Value chain actors				
41	Percentage of suppliers the organization has audited regarding social responsibility in the last year	Promoting social responsibility	Positive	Quantitative
Consumer				
42	Number of consumer complaints	Health and Safety	Negative	Quantitative
43	Presence of management measures to assess consumer health and safety	Health and Safety	Yes	Semi-quantitative (yes/no)
44	Number of defects detected per production batch	Health and Safety	Negative	Quantitative
45	Presence of a mechanism for customers to provide feedback	Feedback mechanism	Yes	Semi-quantitative (yes/no)
46	Publication of a sustainability report	Transparency	Yes	Semi-quantitative (yes/no)
47	Company rating in sustainability indices	Transparency	Positive	Semi-quantitative
48	Possibility of the product to be reused for other purposes	End-of-life responsibility	Yes	Semi-quantitative (yes/no)
49	Infrastructure to dispose responsibly of products components other than landfill and incineration	End-of-life responsibility	Yes	Semi-quantitative (yes/no)
50	Clear information is provided to consumers on end-of-life options	End-of-life responsibility	Yes	Semi-quantitative (yes/no)
Society				
51	Presence of publicly available documents as promises or agreements on sustainability issues	Public commitment to sustainability	Yes	Semi-quantitative (yes/no)
52	Presence of mechanisms to follow up the realization of promises	Public commitment to sustainability	Yes	Semi-quantitative (yes/no)
53	Contribution of the product/service/organization to economic progress	Contribution to economic development	Positive	Semi-quantitative
54	Relevance of the considered sector for the (local) economy	Contribution to economic development	Positive	Semi-quantitative
55	The technology accessible and affordable to developing countries	Technology development	Yes	Semi-quantitative (yes/no)
56	Involvement in technology transfer programs or projects	Technology development	Yes	Semi-quantitative (yes/no)
57	Partnerships in research and development	Technology development	Yes	Semi-quantitative (yes/no)

describe the product's processes with a focus on its social performance or social risk and type II is used to predict the social impacts of the product's processes, with emphasis on characterising potential social impacts (Mattos and Calmon 2023). As no consensus presently exists on cause-effect relationships regarding social issues, and the objective of the study is to evaluate the social impacts of the battery pack, we have used type I characterisation model since it enables the assessment of all the stakeholder groups and their related impact subcategories.

We utilised the methodology proposed by Bonilla-Alicea and Fu (2022) and Shahid (2017), which involves coding each response to the questions individually. The questionnaire responses are assigned numeric codes based on the type of question asked, which can be qualitative, quantitative, or semi-quantitative (Table 4). The score range for each question type is between 0 and 1, with 0 indicating the lowest level of social performance and 1 indicating the highest.

2.3.1 Quantitative indicators

Performance reference points (PRPs) are utilized to compare quantitative indicators with the desired outcomes.

Equations 1 and 2 are used for indicators with positive and negative desired directions, respectively.

$$Indicator_{quant.pos.} = \frac{Indicator_{quant} - PRP_{min}}{PRP_{max} - PRP_{min}} \tag{1}$$

$$Indicator_{quant.neg.} = 1 - \frac{Indicator_{quant} - PRP_{min}}{PRP_{max} - PRP_{min}} \tag{2}$$

2.3.2 Semi-quantitative indicators

We have used two types of semi-quantitative indicators subjected to "yes" or "no" questions and Likert scale-type questions, respectively, with values between 1 and 5 (where 5, very high; 4, high; 3, medium; 2, low; 1, very low). Depending on the Likert scale-type question, an answer of 5 can mean the highest social impact and 1 the lowest social impact or the contrary; 5 is the lowest social impact and 1 is the highest social impact.

To quantify the responses to "yes" / "no" questions, a "yes" answer is assigned a value of 1 and a "no" answer is assigned a value of 0.

For scale-type questions, the normalization procedure depends on the desired direction of the indicator. For example, if the desired direction is positive (where 5 represents the best social performance and 1 represents the worst social performance), the normalization procedure would be calculated as in Eq. 3.

Table 4 Definition of variables and parameters used in Eqs. 1, 2, 3, and 4

Identifier	Definition	Domain
$Indicator_{quant.pos.}$	Normalised value of a quantitative indicator with a positive desired direction/answer.	[0.1]
$Indicator_{quant.neg.}$	Normalised value of a quantitative indicator with a negative desired direction/answer.	[0.1]
$Indicator_{quant}$	Answer to the questionnaire of the quantitative indicator evaluated.	$\mathcal{R}$
PRP_{min}	Minimum value of the PRP used to evaluate the quantitative indicator.	$\mathbb{N}$
PRP_{max}	Maximum value of the PRP used to evaluate the quantitative indicator.	$\mathbb{N}$
$Indicator_{semiq.neg.}$	Normalised value of a semi-quantitative indicator with a negative desired direction/answer.	[0.1]
$Indicator_{semiq.}$	Answer to the questionnaire of the semi-quantitative indicator evaluated.	$\mathcal{R}$
$Indicator_{semiq.pos.}$	Normalised value of a semi-quantitative indicator with a positive desired direction/answer.	[0.1]

Table 5 S-LCA results

Stakeholder category	Normalize impact value										
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	AVERAGE
Worker	0.83	0.72	0.83	0.85	0.75	0.76	0.95	0.92	0.96	0.91	0.85
Local community	1	0.71	1	0.50	0.42	1	0.5	0.80	0.8	0.5	0.72
Value chain actors	---	---	---	---	---	---	---	---	---	---	---
Consumers	0.67	0.83	0.71	---	0.50	1	---	---	1	0.67	0.77
Society	1	0.94	0.50	0.50	0.67	1	0.65	0.67	---	1	0.77

*Cells with three continuous segments indicate participants who did not provide answers

$$Indicator_{semiq.pos.} = \frac{Indicator_{semiq} - 1}{4} \quad (3)$$

On the contrary, if the desired direction of the indicator is negative (1 represents the best social performance and 5 represents the worst social performance), the normalization procedure is calculated as in Eq. 4.

$$Indicator_{semiq.neg.} = \frac{5 - Indicator_{semiq}}{4} \quad (4)$$

2.3.3 Qualitative indicators

Qualitative indicators are scarce; however, there is a comment box available next to each question for respondents to provide additional information.

The qualitative comments and answers were coded and translated into quantitative type. Each question could score ranging from "0" to "1" based on the type and nature of the question. For example, in the workers category, the companies were asked to list social benefits provided to workers; if they answered with less than the mandatory benefits a company must legally provide, the score was "0" and if they answered with more than the mandatory benefit, the score is "1".

In the questionnaire, certain questions remained unanswered, either because they did not apply to the respondent's activities or because the respondent lacked information on those topics. To account for this, the impact score is the average of all the questions answered per stakeholder group.

The threshold established to differentiate between a positive and negative impact is 0.5. A score below 0.5 is considered a negative impact, and a score over 0.5 is considered a positive impact.

3 Results and discussions

The importance of the interpretation and analysis of results is to identify the greatest contribution to social impacts and to propose changes to improve such impacts. We have summarized the normalised results in Table 5 and categorised them by stakeholders to help identify the stakeholder groups most affected by battery pack production. The normalized impact value of each stakeholder group exceeds 0.5, which suggests that the battery design has a positive social contribution.

The worker has the highest positive performance among stakeholders, with an average score of 0.85. This is driven by achieving a score of 1 in 13 out of 23 indicators, and a score between 0.5 and 0.9 in 7 out of 23 indicators. The local community's performance average score is 0.72, with positive valuations obtained in 5 out of 11 indicators scoring 1, and in 2 out of 11 indicators scoring between 0.5 and 0.9. Unfortunately, there are no results available for the impact on value chain actors because most partners who answered the questionnaire do not manufacture physical products, and those who do manufacture did not provide the necessary information.

Consumers, with a performance score of 0.77, achieved positive valuations in 3 out of 8 indicators scoring 1, and in 4 out of 8 indicators scoring between 0.5 and 0.9. A society, with a performance score of 0.77, garnered positive valuations in 1 out of 7 indicators scoring 1, and 5 out of 7 indicators scoring between 0.5 and 0.9.

Based on the results, the lower socially impacted group is the local community with a score of 0.72. For consumers and society stakeholder groups, the results vary lightly, with a same score of 0.77.

We conducted a more detailed analysis of each stakeholder group to better understand the results.

3.1 Stakeholder group: worker

Table 6 shows the results for the worker stakeholder group. Overall, the positive social impact on this group is the highest of all the stakeholder groups with a total score of 0.85, driven by a score of 1 in 13 out of 23 indicators and a score between 0.5 and 0.9 in 7 out of 23 indicators.

The positive impact of this stakeholder group is attributed to several factors: the absence of child labour, indicating a commitment to ethical and responsible practices; the

Table 6 Normalized results for the worker stakeholder group

Impact indicators	Normalize impact Average
Percentage of child labour	1.00
Percentage of children working by country and sector	1.00
Lowest paid worker, compared to the minimum wage	0.89
Number of hours effectively worked by employees (female)	0.69
Number of hours effectively worked by employees (male)	0.78
Possibility of flexible work	1.00
Freedom of workers to end their employment	1.00
Percentage of forced labour by region	1.00
Presence of gender non-discrimination policy	1.00
Presence of a gender committee	0.40
Presence of recruitment policies targeting women	0.40
Presence of maternity leave policies	1.00
Presence of paternity leave policies	1.00
Equal wages for doing the same task	1.00
The potential of technology to affect the health and safety of workers during the manufacturing phase	0.92
The potential of technology to affect the health and safety of workers during the end-of-life phase	0.88
Appropriate safety education and training provided to employees	1.00
Number/percentage of injuries or fatal accidents in the organization by job qualification inside the company	1.00
The appropriate protective gear required in all applicable situations	1.00
Social benefits provided to the workers (e.g. health insurance, pension fund, childcare, education, and accommodation)	0.56
Percentage of permanent workers receiving paid time off	0.00
Number of sexual harassment incidents	1.00
Efforts by the organization to reduce the risk of sexual harassment	0.90

freedom of workers to end their employment if desired, also indicating a respectful and fair approach to employee rights and autonomy; and the presence of gender-non-discrimination policy in place, demonstrating a commitment to creating an inclusive and equal opportunity work environment. This result also entails other positive social aspects due to the presence of both maternity and paternity leave policies, indicating a recognition of the needs of pregnant employees and supporting work-life balance for new mothers, as well as showing commitment to promoting gender equality and supporting fathers in their role as caregivers; equal wages for doing the same task, reflecting a commitment to pay equity and fair treatment regardless of gender or other characteristics; and the absence of sexual harassment incidents and efforts to reduce the risk of sexual harassment, reflecting a proactive approach to creating a safe, respectful and inclusive work environment.

However, some indicators have a relatively low score concerning the best, indicating a need to pay attention to social impacts for improvements:

- **Number of hours effectively worked by employees (female):** the score of 0.69 suggests that female employees are working fewer hours compared to their male coworkers, indicating a potential gender disparity in working hours.
- **Presence of gender committee:** the low score of 0.40 can be attributed to the lack of knowledge and education regarding gender equality promotion, indicating room for improvement.
- **Presence of recruitment policies targeting women:** the low score of 0.40 suggests that there is acknowledgment of a disparity between the percentage of men and women hired, and measures are being implemented; however, there is still room for improvement.

As can be seen, most indicators with a relatively lower score, indicating a concerning social impact, are all related to gender. We will further discuss this later as a part of a gender perspective impact.

3.2 Stakeholder group: local community

Table 7 shows the results for the local community stakeholder group. Results highlight both positive and negative social impacts. The total score of 0.72 is driven by a score of 1 in 5 out of 11 indicators, and a score between 0.5 and 0.9 in 2 out of 11 indicators.

Table 7 Normalized results for the local community stakeholder group

Impact Indicators	Normalized impact Average
Presence of a certified environmental management system	0.78
Levels of industrial water use	1.00
Extraction of material resources	1.00
Individuals who resettle (voluntarily and involuntarily) that can be attributed to the organization	1.00
Management efforts to minimize the use of hazardous substances	0.80
Exposure of the local community to injuries, harm and contagious diseases as a result of the company's activity	1.00
Pollution levels by country	0.16
Percentage of the workforce hired locally	1.00
Strength of policies on local hiring preferences	0.22
Percentage of spending on locally-based suppliers	0.20
Unemployment statistics by country	0.20

The positive impact of this stakeholder group is attributed to several factors: the presence of a certified environmental management system, indicating that the organizations have implemented effective practices to minimize environmental impacts, which can contribute to a better social performance; levels of industrial water use considered not excessive or problematic in terms of its social impact; absence of involuntary resettlement of individuals due to organization's activities and therefore avoiding social disruptions and negative impacts on communities; efforts to minimize the hazardous substances demonstrating a commitment to reduce potential health and environmental risks; absence of risks to the local community in terms of injuries, harm, or contagious diseases due to the company's activities, which represents a prioritization of the well-being and safety of the local population; and high percentage of workforce hired locally, as it supports the local economy, creates employment opportunities, and fosters community development.

However, 4 out of 11 indicators (pollution levels by country, strength of policies on local hiring preferences, percentage of spending on locally based suppliers, and unemployment statistics by country) have a score lower than 0.5 indicating a negative impact.

Increasing spending on local suppliers could have positive social implications, such as supporting local businesses, stimulating economic growth, and fostering community resilience. Another aspect is the high levels of unemployment statistics by a country, which can be improved with projects like this by creating a significant number of employment opportunities in the countries where it is implemented.

The indicator with the highest social impact is the "pollution levels by country". Even though the environmental impact of a product is not solely determined by the country of manufacture, the pollution levels of a country can indirectly contribute to the overall environmental impact associated with a product.

On the other hand, there are some discrepancies in the results of hiring locally, as the indicator of "Percentage of workforce hired locally" indicates that 100% of the participants have a good percentage of local employees but at the same time, the indicator "Strength of policies on local hiring preferences" shows a lack of policies to promote local hiring. We concluded that even though companies are not actively and consciously searching for local employees, they happened to end up having a good percentage of local employees.

3.3 Stakeholder group: consumer

Table 8 shows the results for the consumer stakeholder group. Results highlight both positive and negative social impacts. The total score of 0.77 is driven by a score of 1 in 3 out of 8 indicators, and a score between 0.5 and 0.9 in 4 out of 8 indicators.

The positive impact of this stakeholder group is due to several factors: the absence of consumer complaints; good management measures to assess consumer health and safety; good mechanisms for customers to provide feedback, indicating that the company values customer input and actively seeks to improve its products based on customer experience; the possibility of the product to be reused for other purposes, indicating a consideration for extending the product's lifecycle and reducing waste; availability of infrastructure to dispose responsibly of product components other than landfill and incineration, which shows commitment to reducing environmental and social impact of product disposal; and clear information provided to consumers on end-of-life options.

The only indicator with a score lower than 0.5 is the "Publication of sustainability report", which suggests that companies do not prioritize or actively disclose information through a sustainability report. Publishing such a report can enhance transparency, accountability, and social performance by showcasing the company's commitment to sustainability.

Table 8 Normalized results for the consumer's stakeholder group

Impact Indicators	Normalized impact Average
Number of consumer complaints	1.00
Presence of management measures to assess consumer health and safety	0.60
Number of defects detected per production batch	1.00
Presence of a mechanism for customers to provide feedback	0.86
Publication of a sustainability report	0.40
Possibility of the product to be reused for other purposes	0.60
Infrastructure to dispose responsibly of products components other than landfill and incineration	0.60
Clear information is provided to consumers on end-of-life options	1.00

It must be mentioned that the results of this stakeholder group are not only affected by the subjective value systems used but also by the fact that a lot of the participants in the project offer a service rather than manufacture a physical product which is reflected in some of the low scores.

3.4 Stakeholder group: society

Table 9 shows the results for the society stakeholder group. The indicator "Partnerships in research and development" achieved the highest score of 1. This is a positive result as it promotes collaboration, innovation, and advancement in the field. Out of 7 indicators, 5 have a score that falls within the range of 0.5 to 0.9, which entails positive impacts in the areas of contribution to economic progress and relevance of the local economy. This suggests that projects like this have the potential to generate economic value and contribute to job creation and overall economic development, accessibility of technology to developing countries, indicating the potential for technological advancement and adoption in regions where resources may be limited, and involvement in technology transfer programs.

The indicator "Presence of publicly available documents as promises or agreements on sustainability issues" has the lowest score (0.4), indicating a need for organizations to improve transparency and communication regarding their sustainability commitments. Making these documents publicly available allows stakeholders to better understand the organization's goals and efforts in addressing social and environmental concerns.

3.5 Gender aspects

As a part of the study, we have introduced seven indicators to evaluate the gender aspects and impacts of the project and the results are shown in Fig. 2. Out of seven indicators, four have the highest score indicating the best social performance.

- **Presence of gender non-discrimination policy:** A score of 1 means that 100% of the participants of the project have a gender non-discrimination policy in place, which reflects the commitment to promoting equality and fairness.
- **Presence of a gender committee:** A score of 0.4 means that only 40% of the participants have a gender committee. It implies that there is acknowledgement of the importance of gender-related issues but there is room for improvement.
- **Presence of recruitment policies targeting women:** A score of 0.4 reflects that only 40% of the participants have recruitment policies targeting women. The positive impact of this indicator is attributed to a target of recruiting 2 women per month among one of the partners, but the rest have no recruitment policies targeting women.

Table 9 Normalized results for the society stakeholder group

Impact Indicators	Normalized impact Average
Presence of publicly available documents as promises or agreements on sustainability issues	0.40
Presence of mechanisms to follow up the realization of promises	0.50
Contribution of the product/service/organization to economic progress	0.80
Relevance of the considered sector for the (local) economy	0.77
The technology accessible and affordable to developing countries	0.83
Involvement in technology transfer programs or projects	0.71
Partnerships in research and development	1.00

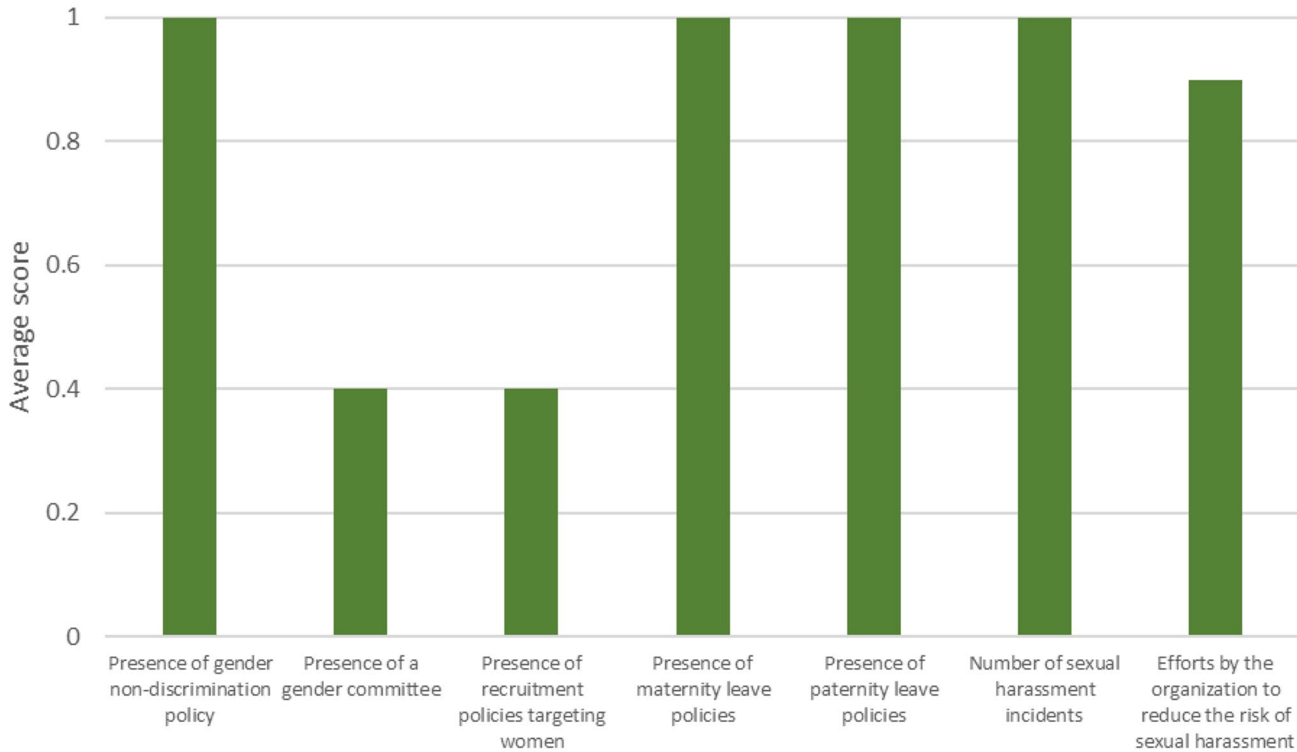

Fig. 2 Results of the gender impacts

- **Presence of maternity leave policies:** A score of 1 implies that 100% of the participants in the project have maternity leave policies which indicates that the organizations recognize the importance of supporting female employees during pregnancy and childbirth. Participants were also asked to provide information regarding the duration of the maternity leave and if it was paid. The answers vary significantly based on the company and the country in which it operates. For example, in two companies, maternity leave is up to 52 weeks, with 12 weeks fully paid, 14 weeks half paid, 13 weeks covered by SMP (statutory maternity pay), and the final 13 weeks unpaid. Whereas in another company, the maternity leave is up to 3 years, with up to 12 months paid (14 months to share with a partner).
- **Presence of paternity leave policies:** Like maternity leave policies, a score of 1 suggests that the organizations provide paternity leave, demonstrating a commitment to supporting work-life balance and gender equality. Participants were also asked to provide information regarding the duration of the paternity leave and if it was paid. It is the same as with maternity leave, depending on the company and the country in which operates the answers vary. In this case, the period of the leave is lower than the maternity leave. For example, it can go from 1 week or 2 weeks to between 120 and 180 days, and in the best scenario, up to 3 years.
- **Number of sexual harassment incidents:** A score of 1 indicates that there have been no reported sexual harassment incidents, reflecting a safe and respectful work environment, which is crucial for the well-being and dignity of all employees.
- **Efforts by the organization to reduce the risk of sexual harassment:** A score of 0.9 indicates that 90% of the participants of the project acknowledge the importance of having a safe work environment and are taking action to accomplish it.

Overall, the results indicate some positive social impacts related to gender policies and initiatives. The presence of a gender non-discrimination policy, maternity and paternity leave policies, and efforts to reduce the risk of sexual harassment demonstrate a commitment to fostering an inclusive and equitable work environment. However, there are areas for improvement, such as strengthening the presence and effectiveness of a gender committee and increasing recruitment policies targeting women to enhance gender diversity in a sector highly led by men.

It should be noted that S-LCA is a highly subjective methodology and that the results can vary significantly based on the person performing the analysis, data collection quality, the impact indicators selected, and the impact assessment methodology.

3.6 End-of-life

To assess the social performance of the end-of-life of the battery, we have introduced three semiquantitative indicators: (i) possibility of the product to be reused for other purposes, (ii) infrastructure to dispose responsibly of products components other than landfill and incineration, and (iii) clear information is provided to consumers on end-of-life options.

We have added two additional indicators to the one indicated in the Methodological Sheets (UNEP 2021), to include information focused on reuse and recycling. This choice comes from the will to address the specific social implications of the battery end-of-life. Indeed, proper end-of-life management of the battery through second use and material recycling not only prevents the possible ambient contamination related to the careless processing and disposal of spent batteries but also reduces the environmental and social risks correlated with the primary material extraction and process of the raw critical materials, positively acting in this way in the second major social hotspot of the battery life (Thies et al. 2019).

The results show an overall score of 0.73 out of 1, indicating good social performance. This is attributed to a score of 1 in the indicator "Clear information is provided to consumers on end-of-life options" and a score of 0.60 in the "Possibility of the product to be reused for other purposes" and "Infrastructure to dispose responsibly of products components other than landfill and incineration" indicators. A score higher than 0.5 in the three indicators reflects the acknowledgement on the importance of this topic.

The introduction of the end-of-life indicators and the focus on the reuse and recycling adopted in this study represent a unicum in the Social LCA of the vehicle batteries and its further implementation with a focus on material value chain and second data from social database represents an opportunity and necessity in the battery social assessment landscape.

3.7 Limitations

The application of the methodology revealed limitations linked to data availability, sample size, data collection, single threshold to categorise impacts as positive or negative, and stakeholder category exclusion.

The study is a result of the ALBATROS project; therefore, data collection and sample size are limited to the expert participants of the project. While it is true that the selected group of experts may not represent the entire spectrum of stakeholders involved in the Li-ion battery sector, we believe that the expertise and insights provided by our selected group of respondents are valuable contributions to the understanding of social impacts in the Li-ion battery sector.

The primary data source was the responses from these experts, who have been directly involved in various stages of the electric vehicle battery value chain. Their insights were complemented, where possible, with secondary data from industry reports, academic publications, and publicly available databases to strengthen the reliability of our findings.

We understand that relying solely on the perspectives of project participants could limit the scope of our assessment and potentially skew the objectivity of our findings. Nonetheless, we want to clarify that this is the first approach to evaluate the social impacts. Therefore, we decided to use the project participants as a source of information to have a first insight into the social impacts of the battery. The results are limited and linked to the ALBATROSS project's battery pack; we do not pretend to generalise all battery packs.

The choice to use a 0.5 threshold to categorise impacts as positive or negative was based on recommendations found in specialized literature, specifically following the guidelines suggested by the United Nations Environment Programme (UNEP) in 2021. This threshold was adopted after a thorough review of similar methodologies in social impact assessment studies, where it was identified as a commonly used cutoff point to differentiate between impacts considered positive and negative. Using a single threshold may not adequately capture the complexity and nuances of some impacts. It is an inherent limitation of this simplified approach, which aimed to facilitate the interpretation and comparison of data.

The absence of available results on the impact on value chain actors lead us to exclude this stakeholder category, which is a limitation of the study, and the results are subjected to it.

4 Conclusions

We conducted an evaluation of the social impacts of lithium-ion battery pack design for electric vehicles (EV) using the social life cycle assessment (S-LCA) methodology and complemented by a gender assessment. To construct the inventory, we obtained data by administering questionnaires to ALBATROSS project partners in accordance with the social UNEP/SETAC S-LCA guidelines. The quality of the results depends on the data collected. Due to the long time and effort that it could have taken to customize the questions to each partner profile, we conducted the questionnaires considering key questions that address stakeholders and impact indicators included in the S-LCA methodology.

The results are average scores converted from the inventory scaled to quantitative, semiquantitative, and qualitative indicators. The range of each score is based on the type of question ranging between 0 and 1, where 0 represents the lowest social performance and 1 represents the best social performance. We calculated the conversion of inventory to quantitative indicators (positive and negative desired direction indicators) to have performance reference points (PRPs) and compared them with the answers. We computed semiquantitative and qualitative indicators as normalised values.

Based on the results of this study, we concluded that the Li-ion battery pack design for EVs has a positive social impact on the stakeholders evaluated. We found a good S-LCA performance for the worker's stakeholder group and positive impacts for the local community, consumer, and society, ranging from 0.77 to 0.85 normalized impact values.

However, three stakeholder groups exhibited negative impacts: local community in pollution levels by country, policies on local hiring preferences, percentage of spending on locally based suppliers, and unemployment statistics by country; consumers in the publication of sustainability reports; and society in the presence of publicly available documents as promises or agreements on sustainability issues.

While the gender analysis reveals positive aspects such as the presence of non-discrimination policies, maternity and paternity leave, and efforts to prevent sexual harassment, some areas require improvement. These include increasing the presence of gender committees, implementing policies targeting women, and continuing efforts to create a safe and equal work environment.

To improve the social performance of Li-ion batteries throughout their life cycle, some key actions could be:

- Develop and enforce policies that prioritize local hiring and create job opportunities for the local community.
- Collaborate with educational institutions and training centres to enhance the skills and qualifications of the local workforce.
- Encourage organizations to prioritize sourcing goods and services from local suppliers.
- Facilitate networking events and platforms to connect local suppliers with larger organizations.
- Ensure transparency and accountability by regularly publishing sustainability reports.
- Increase participation of women and gender balance in funded project teams.
- Gender balance in decision-making structures.
- Institutional change in R&I organizations through gender equality plans, which includes integrating the gender dimension into R&I and teaching content in higher education institutions.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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