Mercator, Fortaleza, v. 24, e24012, 2025 ISSN:1984-2201

NEW METHODOLOGICAL APPROACH FOR THE ANALYSIS OF SOCIAL ASPECTS IN THE LIFE CYCLE ASSESSMENT OF LITHIUM-ION BATTERIES PRODUCTION

https://doi.org/10.4215/rm2025.e24012

Ferreira, E.M. [a*]

(a) PhD in Sanitation, Environment and Water Resources
ORCID: https://orcid.org/0000-0002-1115-8976. **LATTES:** http://lattes.cnpq.br/8657457114953278.

Article history:
Received 06 February, 2025
Accepted 03 June, 2025
Published 10 June, 2025

(*) CORRESPONDING AUTHOR
Address: Vietnamese-German University. Đ. VĐ 4, Thới Hoà, Bến Cát, Bình Dương 75000, Vietnam. Phone: +84 (0) 274 222 0990
E-mail: emferreira.sci@gmail.com

Abstract

The objective of the present work is to propose a new methodology for the analysis of social aspects in Life Cycle Analysis focused on battery production. Moreover, a systematic literature review was carried out, presenting the main existing gaps and opportunities for future research on the social aspects that involve the analysis of the battery life cycle. Scientific articles, mainly those published between the years 2020 and 2024 were analyzed, in addition to the use of gray literature review. One of the main obstacles encountered was the low number of articles published specifically on social life cycle assessment (S-LCA) of batteries, in addition to the existence of a second flaw pointed out by other authors, which is the deficiency in the methodology used in S-LCA. The text presents approach recommendations and suggests future directions. The literature review is the first to specifically evaluate the state of the art of publications on S-LCA and batteries, presenting a suggestion for S-LCA.

Keywords: Lithium-ion battery; Social impacts; Social Lifecycle Assessment.

Resumo / Resumen

NOVA ABORDAGEM METODOLÓGICA PARA A ANÁLISE DE ASPECTOS SOCIAIS NA AVALIAÇÃO DO CICLO DE VIDA NA PRODUÇÃO DE BATERIAS DE ÍON DE LÍTIO

O objetivo do presente trabalho é propor uma nova metodologia para análise de aspectos sociais na Análise do Ciclo de Vida focada na produção de baterias. Além disso, foi realizada uma revisão sistemática da literatura, apresentando as principais lacunas existentes e oportunidades para pesquisas futuras sobre os aspectos sociais que envolvem a análise do ciclo de vida de baterias. Foram analisados artigos científicos, principalemente aqueles publicados entre os anos de 2020 e 2024. Um dos principais obstáculos encontrados foi o baixo número de artigos publicados especificamente sobre avaliação do ciclo de vida social (S-LCA) de baterias, além da existência de uma segunda falha apontada por outros autores, que é a deficiência na metodologia utilizada na S-LCA. O texto apresenta recomendações de abordagem e sugere direções futuras. A revisão de literatura é a primeira a avaliar especificamente o estado da arte das publicações sobre S-LCA e baterias, apresentando uma sugestão para S-LCA.

Palavras-chave: Bateria de íons de lítio; Impactos sociais; Avaliação do ciclo de vida social.

NUEVO ENFOQUE METODOLÓGICO PARA EL ANÁLISIS DE LOS ASPECTOS SOCIALES EN EL ANÁLISIS DEL CICLO DE VIDA DE LA PRODUCCIÓN DE BATERÍAS DE IONES DE LITIO

El objetivo de este trabajo es proponer una nueva metodología para analizar los aspectos sociales en el Análisis del Ciclo de Vida enfocado a la producción de baterías. Además, se realizó una revisión sistemática de la literatura, presentando las principales brechas existentes y oportunidades para futuras investigaciones sobre los aspectos sociales involucrados en el análisis del ciclo de vida de la batería. Se analizaron artículos científicos, principalmente aquellos publicados entre 2020 y 2024. Uno de los principales obstáculos encontrados fue el bajo número de artículos publicados específicamente sobre la evaluación del ciclo de vida social (S-LCA) de baterías, además de la existencia de una segunda falencia señalada por otros autores, que es la deficiencia en la metodología utilizada en S-LCA. El texto presenta recomendaciones de enfoque y sugiere direcciones futuras. La revisión de la literatura es la primera en evaluar específicamente el estado del arte de las publicaciones sobre S-LCA y baterías, presentando una sugerencia para S-LCA.

Palabras-clave: Batería de iones de litio; Impactos sociales; Evaluación del ciclo de vida social.

ARTICLE

INTRODUCTION

Batteries make modern life possible and help to reduce the need of fossil, with some of the impacts of this use still unknown. Reducing the use of fossil fuels has come to be seen to some governments and public managers as one of the most important measures to be taken by society. Mainly starting in the 2000s some countries have formulated plans to reduce their national emissions with a view to achieving carbon neutrality (and other greenhouse gases) by 2050 or 2060 (CHAVES, 2021).

Specifically, about electric mobility, batteries play a key role as can be considered one of the most important and highest-cost elements in the electric vehicle (EV) value chain. Unlike vehicles with internal combustion engine, which depend on fossil fuels or biofuels to obtain their energy, in EVs the battery cells occupy this central role (BERMÚDEZ-RODRÍGUEZ and CONSONI, 2020).

The global battery market is expanding, especially with the advent of electric cars, which has affected prices, which have ultimately become cheaper for the end consumer. In 2024, electric car sales increased 25%, totaling 17 million units worldwide, with demand surpassing 1 terawatt-hour (TWh). This is a historic milestone for the industry. As a result, the average price of a battery used in an electric car has fallen to less than US$100 per kilowatt-hour. This is seen as a limit in terms of cost competition with conventional battery models (IEA, 2025). Of course, all this production has a huge social impact in countries that still use slave labor and very low levels of worker protection for the extraction of raw materials and production of batteries. More studies are needed on these social impacts involved in battery production.

Focusing on the social impacts of the production of batteries, it can briefly mention the problems related to the extraction of raw materials, the possible occupational risks and the impacts that exist during recycling. In a study carried out on the health impacts of workers who deal with electric recycling batteries, one of the conclusions of the authors is the possibility of probability of lead accumulation in the bones of most of the workers, which can cause damage to health, with manifestation in the medium and long term. Moreover, when not done appropriately, battery recycling can contaminate the air, soil, and water, not only at the processing site, but also in surrounding regions, with the residue remaining on site even after the end of the activity (MINOZZO et al., 2008).

One of the possibilities in trying to control the environmental and social impacts of this technology is the use of certifications, e.g., the International Organization for Standardization (ISO) which generally the methodology consists in: i) Understanding the organization´s value chain; ii) Identify the impacts of standards; iii) Analyze the value drivers and determine the operational indicators and iv) evaluate and calculate the results (GIOVANETTI and CLETO, 2018). To ensure the comparability of life cycle assessments, the ISO has developed two complementary standards: the principles and framework for life cycle assessment are described in ISO 14040; the specific requirements are set out in ISO 14044. At the ISO is possible to see the definition and what is necessary for an LCA, and the inventory of it, the impact assessment, how to interpret it, report and review, and the limitations of all the phases. Furthermore, what to consider when making a choice (ISO, 2024).

The LCA approaches are based on the three main pillars of sustainable development and its concept. The approaches are: i) Life Cycle Assessment (LCA); ii) economic: Life Cycle Costing (LCC), and iii) social: Social Life Cycle Assessment (S-LCA). These methodologies can evaluate potential negative and positive interferences of something, considering its social, environmental, and economic aspects, from cradle to grave, or from the extraction of raw materials until the end of the use (REBOLLEDO-LEIVA et al., 2023).

Social aspects are extremely important to consider protecting the lives of people involved in processes related to the production of a certain product, e.g., batteries, and of the different stakeholders which can be influenced by the technology. The evaluation of social impact is important for the consumer, the companies, researchers, and manufacturers, and all the stakeholders connected to a certain process, to understand the consequences of the use of their products on society and to inform and address the consumers to more ethical choices.

Social aspects of LCA still represents a large research gap. The social part of sustainability needs to be better studied, which in LCA the production and end-of-life still represents a gap (BORRI et al., 2024). Some studies are focused on modelling of the social aspects, but this increases subjectivity, resulting in poorly conducted S-LCA. It is necessary to think about extracting primary data as well, e.g., through in-depth interviews. To some extent, the collection of primary social data can be complex and not accessible (HADDAD et al., 2023).

In this research, key aspects will be discussed when dealing with social impacts in the life cycle of lithium-ion batteries, especially the community directly affected by this life cycle, including workers and society, safe and healthy living conditions, access to material resources, economic development, health and safety of those involved in the activities, corruption factors, small-scale agricultural production, local employability, cultural heritage, equal opportunities and discrimination (DOMINGUES et al., 2024).

The work is justified mainly by the low number of publications that specifically address the social aspects involved in battery production, which still uses "dirty" labour for the extraction of metals such as niobium and lithium. In addition, another essential justification is the inclusion of a step-by-step guide in the section "A new approach for the analysis of social and environmental aspects involved in battery production".

Following the above, the objective of the present work is to propose a new methodology for the analysis of social aspects in Life Cycle Analysis focused on battery production, together with a bibliographical review of articles published in the last years on S-LCA of batteries, presenting the existing blind spots, carrying out a critical analysis of the materials and bringing recommendations for future studies.

MATERIAL AND METHODS

The study is a systematic review with highlighted critical analysis which was based on the search of literature published in peer-reviewed resources mainly scientific research articles and review articles, including books, and book chapters. The initial search keywords were: i) Batteries production; ii) Sustainable Development Goals (SDG); iii) Life Cycle Assessment; and iv) Social Life Cycle Assessment.

After a first screening new keywords were chosen: LCA and Circularity and Raw materials extraction for batteries production and recycling. Most of the papers presented in this review were published in English during the last decade, specifically in the last five years. The articles are derived from certified data bases (e.g., Web of Science, Science Direct, SciELO and Scopus).

Proceedings, statistics, and reports from international entities (e.g., World Health Organization (WHO), United Nations Environment Programme (UNEP) and European Environment Agency (EEA) were further searched to confirm and/or extract certified databases. The software EndNote was used as a support for the paper's selection. It was used the "Document Search" of ScienceDirect database to quantify the number of publications during the last years. Using the ScienceDirect and Scopus search tool, the following filters were applied:

i. Keywords: i) Batteries production; ii) Global Reporting Initiative (GRI); iii) Sustainable Development Goals (SDG); iv) Life Cycle Assessment; and v) Social Life Cycle Assessment.

ii. Article type: Review articles and Research Articles.

iii. Subject areas: Energy, Material Science, Engineering, Environmental Science, Chemical Engineering, Chemistry, Decision Sciences and Social Sciences.

iv. Access type: Materials available in the data bases mentioned bellow.

The literature review considers the strengths and gaps of the topic, catalyzing a dialogue on the need to better include and evaluate the social aspects of the battery industry. The following figure presents the main steps used in the study (Figure 1).

In the section "Gaps identified in the literature regarding the lack of information about LCA and batteries and future directions", the work presents a proposed methodology for analyzing social impacts in industries, considering a step-by-step process that also includes the inclusion of environmental aspects, something not found in the articles used in the literature review. This is one of the novelties of the paper.

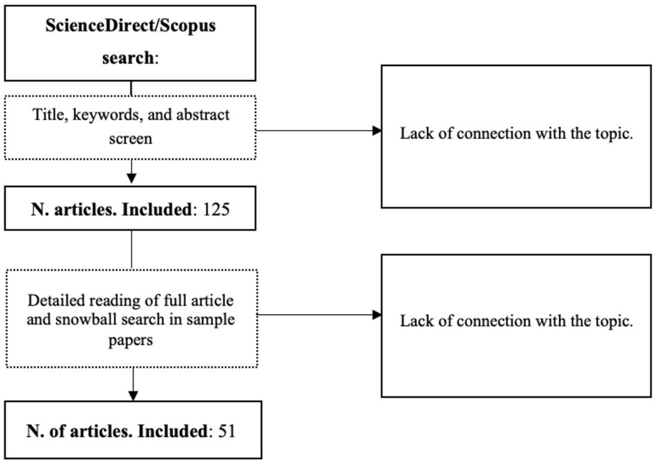

Figure 1 - Flow chart: review process of selected article.

The review carefully introduces the prominent results of scientific reports without repeating their conclusions. The following graph was created to represent the number of publications about S-LCA and batteries between 2020 and 2024. In addition to using the Science Direct filtering tool using the words "Social Life Cycle Assessment" and "batteries", a second selection was made based on reading the titles of the review and research articles (Figure 2):

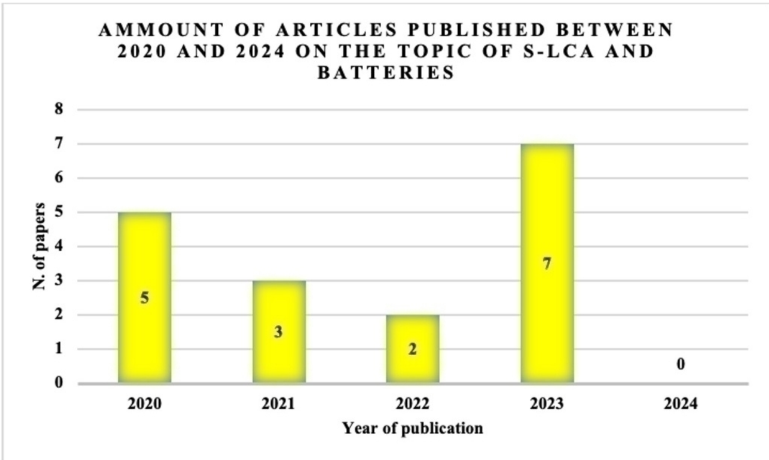

Figure 2 - Representation of works published between 2020 and 2024, directly or indirectly connected to S-LCA and batteries. In the year 2024, the number 0 corresponds to the data collected until May of the same year. Source: Corresponding author (2024).

During the article, an analysis is made of the main topics presented, but here, as can be seen in figure 2, there is a limitation in the low volume of works published on social aspects involving LCA of batteries. One of the possible reasons for this is the need for greater maturity regarding the environmental impacts of batteries, something that perhaps became more prominent after the emergence of electric vehicles. Even though we are aware of the existence of other batteries, the work is focused on lithium batteries and their modifications, these being the most common types.

SUSTAINABLE DEVELOPMENT GOALS APPLIED TO PRODUCTION BATTERIES

The different environmental conferences that took place from the 70s onwards brought the creation of international agendas and protocols to slow down negative impacts related to climate change. One of the results are the Sustainable Development Goals (SDGs) of the United Nations. 17 goals are pointed, here being considered: 1) No poverty; 2) Zero hunger; 3) Good health and well-being; 4) Quality education; 5) Gender equality; 6) Clean water and sanitation; 7) Affordable and clean energy; 8) Decent work and economic growth; 9) Industry, innovation and infrastructure; 10) Reduced inequalities; 11) Sustainable cities and communities; 12) Responsible consumption and production; 13) Climate action; 14) Life below water; 15) Life on land; 16) Peace, justice and strong institutions; and 17) Partnership for the goals (UNITED NATIONS, 2024).

Some goals are important to be highlighted about LCA and batteries: 7, 8, 9, 11, and 12. The production, post-processing, use and end-of-life of a battery has a direct impact in the industry and economy. The technology needs to be together with the improvement of life quality, not only thinking about economic development, but assuring the reduction of poverty and good health and well-being.

There is a bidirectional relationship between sustainable development and economic growth, which e.g., European Union (EU) try to make it work together. Energetically, it as a fact that more appliances bought and used in a daily basis increases the demand for power (ZAKARI et al., 2022).

When the SDGs were created, the goal was equalized wellbeing, addressing the social and environmental components, but it is still seen inequalities and several economies struggling to address properly what was agreed, including in the EU. A way to monitoring it is through the Sustainable Development Report. Every country should have it and should monitor its actions (DEL-AGUILA-ARCENTALES et al., 2022).

Monitoring SDG indicators is vital to drive effective action toward environmental sustainability. In the EU, the latest Eurostat monitoring report on progress towards the SDG since 2020, showed that over the past five years, it happened some improvement in the data availability mainly about water management, still lacking other goals (NAKHLE et al., 2024).

The Agenda for Sustainable Development (2015-2030) brings lessons from the Millennium Development Goals (MDG), recognising that the SDGs are not possible to divide it is necessary to integrate them in the daily bases (Article 13, 2030 Agenda), which is seeing as green washing in some cases. The decisions must be inclusive, participatory, and representative in the process of decision and to all the stakeholders. The 17 SDGs and their 169 associated targets are complex an interlinked system (BREUER et al., 2023). With the implementation period for the SDGs being from 2015 to 2030; in 2024 the world is nearly going to the limit about the implementation time. It is necessary to appraise and scrutinize SDG performance of countries across the globe (PRADHAN et al., 2023).

The following figure presents examples of the main points involved in the sustainability process, connecting with the battery life cycle and the breaks that may exist, making the process sustainable or unsustainable (Figure 3):

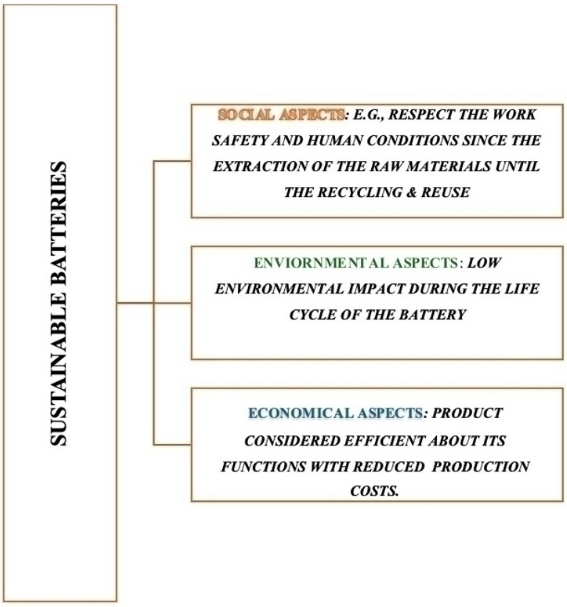

Figure 3 - Main aspects to be considered for a sustainable life cycle of a battery. Source: Corresponding author (2024).

SOCIAL LIFE CYCLE ASSESSMENT

The life cycle of a product can be broadly divided into i) Primary material production; ii) Feedstock material production; iii) Production; iv) Post-processing; v) Use and vi) End-of-life (KOKARE et al., 2023). This cycle goes beyond the present and considers the past and the future, i.e., the entire circle of an item. Usually, every production has several emissions in every phase, this requires energy, water and effort. Not only objects, but human beings also have impact in the environment during our life cycle (SAMANI, 2023).

The goals of the 2030 Agenda, intend to create a more equalitarian world, in which the society and the economies can contribute to each other for the environmental protection. Industrially, every production step needs to be evaluated and considered from the material extraction until the end of life (MÁRMOL et al., 2023). The product LCA is a significant source of environmental, social, and economic impacts. It is important to see the product. This makes us reflect about how approach, transform and analyse the systems in a circular way (SAMANI, 2023). To a certain activity be considered sustainable it is necessary to think about the social, environmental, and economic aspects. Moreover, such aspects need to be assessed and controlled.

When thinking about assessment, all the stakeholders need to be considered. The focus of a S-LCA is people and its methods to assess it focus on the planning and project stage, considering what can be a positive or negative impact (LARSEN et al., 2022). COSTA et al., (2022) includes as indicators: i) Number of persons engaged (includes both employees and self-employed workers); ii) Number of employees (includes only employees); iii) Labour compensation (includes wages and social contributions of both employees and self-employed workers), and compensation of employees (includes wages and social contributions of employees). Self-employment is usually considered in economies with an informal sector, but small business should be part of it.

Tsalidis et al., (2023) point as extra indicators for a S-LCA. Some of them are labour rights (freedom of association and collective bargaining), fair salary, working hours, occupational safety, circular economy, employment, degree of integrated water resources management (IWRM) implementation, basic sanitation activities, annual freshwater withdrawals (% of internal resources), exports-to-imports ratio, and manufacturing employment as a proportion of total employment (TSALIDIS et al., 2023).

The UNEP and the Society of Environmental Toxicology and Chemistry (SETAC) published the Guidelines for Social Life Cycle Assessment of Products, which are crucial in guiding the assessment of social impacts throughout the life cycle of products. These guidelines aim to promote improvements in social conditions for stakeholders involved in the life cycle of products, emphasizing the importance of considering social and socio-economic aspects alongside environmental and economic factors (FINKBEINER et al., 2010).

The guidelines provide a structured methodology for S-LCAs, offering a framework for evaluating the positive and negative social impacts of products on society. By defining key concepts and methods for SLCA, the UNEP/SETAC guidelines serve as a foundational document that helps standardize the assessment of social impacts in life cycle assessments. The guidelines highlight the significance of assessing social equity, working conditions, quality of life, and other social aspects to support decision-making processes aimed at enhancing sustainability and promoting social responsibility in product development and management (BENOIT et al., 2010).

To sum up, even if a product is environmentally friendly, the society needs to be considered. All human beings involved in the chain of creation, use and disposal must be respected and protected from any impact, here considering what may be seen as positive for the industry, but for the people of the region, perhaps not.

LCA AND CIRCULARITY: AN OVERVIEW

The production of packaging and waste arising from it has generated a considerable volume of waste that sometimes cannot be eliminated and treated using existing technologies. Here, as one of the solutions, the concept of circular economy (CE) comes into play, which helps to reinsert certain materials into the production chain.

In the last decades, because of the need of investments in green ideas, a strong research and political interest in the circular economy has been developed. For some authors, the multidisciplinary of environmental management topics, its systematic and procedural complexity creates a space for exploration of many dimensions and for revealing the extensive economic and noneconomic potential of the introduction and use of the circular economy in the ideas of different sectors in society (SKARE et al., 2024).

Circularity is necessary at different levels, including internal. To organizations is usually an issue to adapt to circularity, considering the need to change some process, for example, the disposal of its waste. In a study about circular economy, it was pointed as difficulties: i) Specific transitions; ii) Internal communication management and decision-making within the boundary of procurement to equipment forfeiture, and, e.g., iii) The use of Lewin's change management model to create actionable steps toward improved circularity (MCMAHON et al., 2024).

As before mentioned, the circularity can be accessed with several factors, e.g., labour conditions, pollution control, water and energy consumption, waste management, and product design. A more complete approach considers all the phases, which when lacking data need to be addressed and solved through another method. In addition, when evaluating the circularity of the overall supply system it can result in a better result of the assessment (SAZDOVSKI et al., 2024).

It is doable to join LCA and circularity, in which both LCA and CE have merits and receive a lot of attention because of the ideas of sustainable development, and sometimes green washing. Currently assessments are done separately. It is possible to run both circularity and LCA calculations and compare its results, e.g., with the use of openLCA, which is just one of the currently used tools. Specifically for batteries, investigations over the cradle-to-grave datasets of a Lithium-ion battery show that the amount of virgin material extracted from earth is 43 times bigger than the weight of the battery, and that the overall waste produced is 92 times the weight of the battery (PALOMERO et al., 2024). With this conclusion, it is shown again the need of the use of raw materials from recycled batteries, something discussed in the next topic.

BATTERIES PRODUCTION

Devices which convert chemical energy into electric energy are part of our modern lives and necessary, even to communities with a low access to technology. The enlarging of the world population changed the need for energy, increase it, and disrupted between the supply and the demand. With the climate crisis, the power production is switching to greener options, such as renewable sources and battery energy storage systems (BESS) in the intend to solve this rising issue (SHAFIEI et al., 2024).

When it comes to lithium-ion batteries, the main types and their respective durability are i) Lithium Iron Phosphate (LiFePO4): 2000-4000 cycles; ii) Lithium Cobalt Oxide (LiCoO2): 300-500 cycles; iii) Lithium Manganese Oxide (LiMn2O4): 500-1000 cycles; iv) Lithium Nickel Cobalt Manganese Oxide (LiNiCoMnO2): 800-2000cycles; v) Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2): 300-500 cycles; and vi) Lithium Titanate (Li4Ti5O12): 10,000 cycles or more (HUNTKEY, 2024).

To avoid moisture, the production needs to be enrolled in a dry room. This stage requires complex and energy-intensive technical building services (VOGT AND HERRMANN, 2021). However, it does not suit for all the types of electrodes. As they can induce high bending stress onto the electrodes and potentially damage the electrode coating (BOESELAGER et al., 2022). Electrodes and electrolytes productions are critical factors in cell production which is why different process must be carried out under cleanroom conditions and, accordingly, digitization of the building can also be useful in optimizing the product (Kies et al., 2022).

The Li-ion and post-lithium batteries are considered the evolution of technologies used before for electric storage, but a simple extrapolation of the established battery and the dedicated production facilities will not allow to meet targets on sustainability (e.g., green energy, green economy, and social balance), safety (e.g., liquid/solid electrolyte and growth of dendrites), cell performance (e.g., capacity and fast charging) and their production concerning operating media consumption and energy supply (BUCK et al., 2023).

Before integration into production, a configuration containing set process parameters must be derived, which leads to robust product features while fulfilling sustainable targets. To ensure the consistency of developed targets during production, a controller must maintain set parameters in real-time with respect to minimal manufacturing impacts (ROHKOHL et al., 2023).

One of the challenges of battery production is the reduction of CO2 emissions and the need to integrate recovery. This can recuperate part of the raw materials used in the future batteries and enables an extension of the product lifetime and a reduction of the demand for new raw materials. A concurrent process is to empower production processes with renewable energy with a lower CO2 footprint (SCHELLER et al., 2023). Figure 4 presents the main stakeholders involved in the battery life cycle and in figure 5 it is possible to see an example of battery production at a lab scale level.

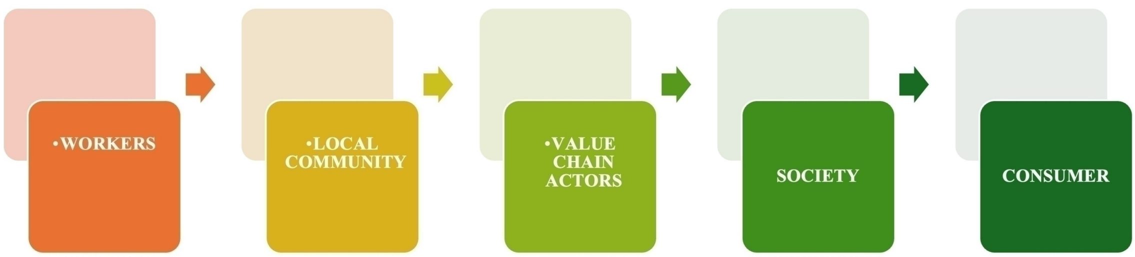

Figure 4 - Main stakeholders involved in the battery life cycle. Source: Corresponding author (2025).

Figure 5 - Laboratory-scale pouch for cell assembly. From left to right, the first step is pouch formation, the second is electrode cutting, followed by electrode stacking and ultrasonic welding, followed by heat sealing, and the last step is vacuum sealing. Source: Image courtesy of the Centre of Polymer Systems, Tomas Bata University in Zlín, Czechia (2024).

GAPS IDENTIFIED IN THE LITERATURE REGARDING THE LACK OF INFORMATION ABOUT LCA AND BATTERIES AND FUTURE DIRECTIONS

Environmental assessments are essential in preventing environmental disasters. Multidisciplinary teams need to be considered, taking the problem into a holistic analysis. In public policies it is needed is to go beyond what the law recommends, creating it in countries that are weak in the subject and do not consider environmental crime as a penalty. Government, industry and society need to act together.

The degradation caused by environmental destruction is no longer part of the future, but of the present. The effects of uncontrolled human consumption and production without social and environmental responsibility have placed society on the edge of survival, with floods, droughts, species extinction, hunger, poverty, extremely low/high temperatures, in some cases irreversible, becoming more and more frequent environmental disasters. The necessary actions are immediate (JAYASANKA et al., 2024). The industrial revolutions brought a huge leap in people's comfort and quality of life, but society needs to move beyond the idea of production at any cost.

With the research done in the recent decades, it has been proven that several components have accumulated in the environment, burdening populations with exposure to chemical and non-chemical stressors. In general, those most impacted by this are populations with lower purchasing power, where social, economic and environmental problems are directly connected to each other (TULVE et al., 2024).

It is still necessary to publish and deepen the social aspect of batteries. As demonstrated in figure 2, few studies exist on the topic and another important point to emphasize is the need to combine different methodologies for the evaluation of Social Life Cycle Assessment, for example, not only focusing on the use of software, but also with the use interviews.

Table 1 presents the main aspects that still need to be addressed and worked on about batteries and analyze the life cycle of social aspects and table 2 details some of the methods used in the papers found for the S-LCA analysis. Figure 6 shows an example and suggested study flowchart for S-LCA in battery industries.

Author and year	Drawbacks
Haddad et al., 2023	*"Some studies are focused on modelling of the social aspects, but this increases subjectivity, resulting in poorly conducted S-LCA".*
Scheller et al., 2023.	*"Need to integrate recovery [...]. A second point is to empower the production process with renewable energy with a lower CO2 footprint [...].*
Kouloumpis et al., 2023.	*"The disposal of electrical and electronic equipment at their end-of-life is a relatively new one compared to the problems of managing conventional types of waste and considered an issue. Small electronic devices which use batteries are useful, but its relatively life spam bring a considerable amount of waste with a complex and expensive recycling technology. Some materials are toxic with a high potential of contamination".*
Maisel et al., 2023.	*"The supply of raw materials is the bottle neck for electric cells. With the new tendencies of electromobility and the resulting increase in using potentially critical raw materials for batteries, it is necessary to think about from where and how to extract raw materials".*
Abdelbaky et al., 2023.	*"There is a lack of analyses of the environmental impacts in some processes, e.g., hydrometallurgical processing of slag from pyrometallurgical recycling".*
Leal et al., 2023.	*"Other challenges of the recycling of batteries are: i) Inefficient selection collection; ii) Pretreatment process problems; iii) Pricy metal extraction process; iv) Studies on recycling focused on cathode materials; v) Lack of popularization and subsidies to adapt recycling processes or to cover investment costs hinder the development of a circular economy; and vi) Lack of policies and regulations.*
Tancin et al., 2024.	*"The manufacturing line might utilize a vacuum system with a cyclone separator to allow continuous collection of debris during graphite or nickel manganese cobalt oxide laser ablation".*

Table 1 - Main issue about batteries and its LCA found in the literature detected during the construction of the text. Continue. Source: Author (2024).

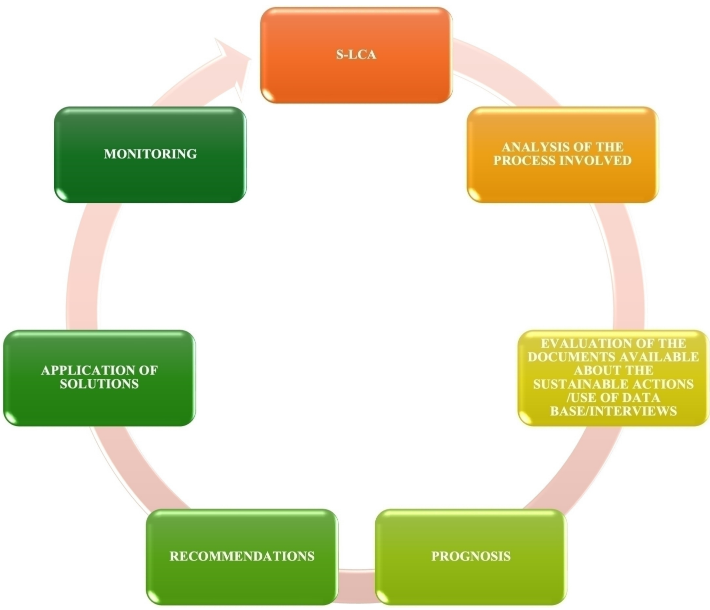

Figure 6 - Suggestion of approach when evaluating S-LCA of batteries. Source: Corresponding author (2025).

Author and year	Title	Method used
Shi et al., 2023.	Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials	By introducing trade data, the study combined supply concentration and S-LCA to explore the social risk profile of lithium iron phosphate battery production by referring to external supply data and the SHDB. Herein, the authors visualized the 2020–2021 related supply faced by China, Japan and South Korea by connecting materials with specific sources. Two S-LCA schemes based on the single dominant supply source and multiple supply sources were demonstrated separately and compared with each other. As social topics for each group of stakeholders were manifold, divided into several impact categories, e.g., fair salary for workers.
Springer and Zapp, 2024.	Potential Social Impacts regarding working conditions of Fuel Cell Electric Vehicles	It was used impact categories, which consists of a grouping of one or more indicators, e.g., living wage, minimum wage etc., to measure the impact. Building the social life cycle inventory was the second phase of the S-LCA. During the third phase, the social life cycle impact assessment was conducted.
Bamana et al., 2021.	Addressing the social life cycle inventory analysis data gap: Insights from a case study of cobalt mining in the Democratic Republic of the Congo	The study was divided in three main steps: Goal and scope definition (selection of stakeholders), Life Cycle Inventory Analysis (data collection focused on Carbon dioxide emissions and minimum wage), LCA impact and interpretation.
Toosi et al., 2022.	A novel LCSA-Machine learning based optimization model for sustainable building design-A case study of energy storage systems	The proposed model consists of sets of mathematic equations to describe LCSA pillars of buildings, including Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA) as the intermediate indices.
Toosi et al., 2022.	A novel LCSA-Machine learning based optimization model for sustainable building design-A case study of energy storage systems	A final LCSA index is provided to describe a design scenario's performance from an LCSA perspective using the authors' new formulation and weighting method. The model is also integrated into the optimization process and enhanced with Machine Learning (ML) methods to accelerate the design-assessment process while preserving its accuracy. Finally, given the transition towards buildings' electrification by Renewable Energy Sources (RESs), as a supportive technology, the size-optimization of a residential building's short-term thermal and electrical energy storage systems (ESSs) is chosen to demonstrate the model's capabilities.

Table 2 - Some of the methods used to evaluate S-LCA. Continue. Source: Author (2024).

To evaluate the social aspects of any point, it is important to consider not only the use of available databases and software, but to try to access the reality as close as possible to the group studied, in the case of the present articles, companies involved in the battery production process. Figure 5 provides an example of an approach that could be adopted, accessing the population and society directly. The use of databases should be part of the diagnosis, but not the main source of information. When it comes to batteries, more studies need to be done on the impacts of extracting raw materials in areas of extreme poverty and how to use recycling technologies more efficiently.

In research on the social impacts of technologies, it is necessary to go in-depth into industrial processes, visiting the different problems that local and regional society may have. When it comes to cradle to cradle, the extraction of raw materials needs to be evaluated, improving the design of products in a way that facilitates recycling and extraction of by-products that can be reused, in the case of batteries, especially the higher value metals, which become increasingly scarce in nature.

The main criticism of this work focuses on the need to publish more studies that explore the socio-environmental assessment of the chain that involves batteries and the need for studies that analyze the processes holistically. Zhou et al., (2024) points in his work that the investigations are still limited, lacking more knowledge about mining process, the selection of by-products, which method of recycling and which environmental categories to choose for assessment. The research done is isolated and brings to fragmented comprehension about the impacts of lithium-ion battery production.

A NEW APPROACH FOR THE ANALYSIS OF SOCIAL AND ENVIRONMENTAL ASPECTS INVOLVED IN BATTERY PRODUCTION

It is essential to focus on the human aspect of battery production. The European Union country has begun this process, but this is still lacking in production in Chinese factories. It is necessary to analyze the processes involved in the business. Each industry is different, and a good assessment includes evaluating documentation and reports on the company's activities that in some way may affect people's quality of life. This phase should be in the beginning of the S-LCA, and it is essential in characterizing the enterprise and needs to be done as detailed as possible, being the basis for a well-done S-LCA. The firm needs to have documented everything involving its processes and the characteristics of its suppliers. Some questions can help in this phase, e.g., Is there any program focused on this subject? Does the company have control over its suppliers? Currently, it is essential to carry out interviews, in which companies that have ISO certification have greater control and something more organized in their systems.

Much of what we see is focused on the safety part of the work, but it is good to keep in mind that social aspects are not just that. After collecting information together with the company, carrying out interviews, visits and meetings with those responsible for the social part and using gray literature and databases, a prognosis of the company's situation can be made. At this point, the main problems are highlighted, the existing flaws that could cause financial and environmental liabilities in the future and what needs to be modified in the short, medium and long term. The prognosis phase is extremely important and needs to be directly linked to the objectives raised in the diagnosis of the company's activities and social impacts.

The forecast can be presented in the form of slides, or even in a booklet, which is easy to understand for all employees and stakeholders involved. Here it is necessary to use graphics and visual materials that make the language as accessible as possible. Some of the mistakes made at this stage are not including all employees or even presenting the results in inaccessible and elaborate language.

With the prognosis, recommendations must be made. What is good needs to be optimized, and what is badly needs to be modified and adapted so that it becomes socially sustainable. An example of solutions is changing suppliers, or even the use of technology that allows the recycling of materials present in batteries. Here financial investment from the company becomes necessary, which must be open to new ideas that will make its processes cleaner. The return for this can be through green marketing, which, unlike what is seen in some companies, will not use green washing.

The next phase is to put into practice what was presented in the prognosis. The solutions presented will be adopted in the company's processes, which sometimes need to be completely restructured and as previously mentioned, the quickest way (not always the easiest) is to change suppliers, in the case of batteries, of raw materials that are still produced with labor considered slavery. An alternative for the insertion of recycled materials is outsourcing, in which a contracted company specializing in battery recycling would extract and process the materials. There are companies that specialize in this and sometimes transferring this type of work is less expensive than having the battery producer do it itself.

The last part, which will somehow feed back into the idea cycle and process optimization, is monitoring. Here it is appropriate to monitor at least every six months, not only the profits and losses that the company has with the adoption of new technologies, but also an analysis of what did not work and what needs to be adapted again. Figure 7 presents the life cycle of a Lithium-ion battery.

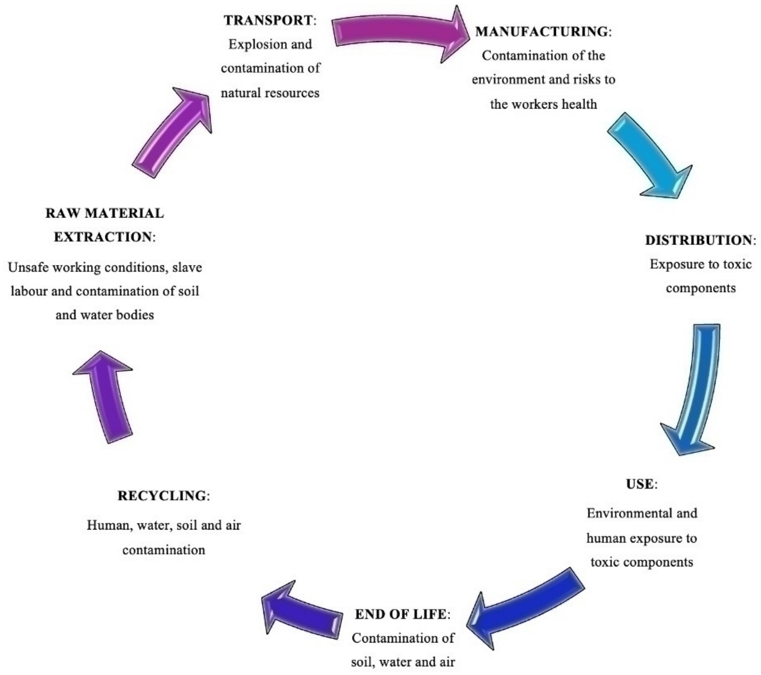

Figure 7 - Battery life cycle and the environmental and social risks related to it. Source: Corresponding author (2025).

CONCLUSIONS

The inclusion of social aspects in industries needs to be seen beyond the mere obligation to comply with the requirements of economic blocs, such as the European Union, but to act in a conscious and progressive way for the quality of life of the people involved in the entire life cycle of a product. When we think about sustainability, it is impossible to consider something sustainable, where its production is based on subhuman conditions.

The present work brought a new approach to studies that include social aspects in life cycle analyses, in addition to pointing out directions for future research on what needs to be explored when dealing with batteries. One of the main bottlenecks is the inclusion of more in-depth analyses, not based only on available databases, but on the concern with the creation of primary data that directly access the realities in question. Some aspects need to be addressed here, namely:

i. Greater integration between modeling and primary studies.

ii. The need to include ways of material recovery.

iii. Improvements in existing techniques and technologies for waste management.

iv. Improvements in raw material supply chains.

v. Use of production techniques that facilitate recycling.

vi. Improvements in the work environment of the industries.

Sustainability and social justice need to be seen not as obstacles to the economy, but as a force to improve people's lives, creating a fairer society that is aware of the consequences of its consumption. Battery production has great potential for this, but its impacts on societies, e.g. China and Congo, need to be taken more seriously.

Improving communication channels is a key factor when it comes to respecting and protecting the rights of local communities. This may require the use of the law, in which companies are obliged to respect the rights of vulnerable communities and populations.

MERCATOR

ARTICLE

REFERENCES

Abdelbaky, M., Schwich, L., Henriques, J., Friedrich, B., Peeters, J. R., Dewulf, W. Global warming potential of lithium-ion battery cell production: Determining influential primary and secondary raw material supply routes. Clnr. Log. and Sup, Ch. 9, 100130, 2023.

Bamana, G., Miller, J. D., Young, S. L., Dunn, J. B. Addressing the social life cycle inventory analysis data gap: Insights from a case study of cobalt mining in the Democratic Republic of Congo. One Earth, 4, 1704-1714, 2021.

Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T. The guidelines for social life cycle assessment of products: just in time! The Int. J. of LCA, 15, 156–163, 2010.

Bermúdez-Rodrígues, T and Consoni, F. L. An approach to the dynamics of the scientific and technological development of lithium-ion batteries for electric vehicles. BR. Innovation J. Campinas (SP), 19, e0200014, p. 1-33, 2020.

Boeselager, C., Kapelar, M. O., Dröder, K. Multi-Body Simulation of a Novel Electrode Stacking Process for LithiumIon Battery Production. Procedia, 112, 519-524, 2022.

Borri, E., Zsembinszki, G., Cabeza, L. F. Evaluation of the social impact of an energy system for residential heating applications based on a novel seasonal thermal energy storage. J. of En. Storage, vol. 86, 111210, 2024.

Breuer, A., Leininger, J., Malerba, D., Tosun, J. Integrated policymaking: Institutional designs for implementing the sustainable development goals (SDGs). Wld. Dev, 170, 106317, 2023.

Buck, F., Imdahl, C., Dilger, N., Zellmer, S., Herrmann, C. Simulation-based planning of process chains and production environments for solid-state batteries. Procedia, 116, 426-431, 2023.

Chaves, A. S. Clean electricity technologies can solve the climate crisis. BR. J. of Phys. Teach, vol. 43, e20210361, 2021.

Costa, D., Quinteiro, P., Pereira, V., Dias, A. C. Social life cycle assessment based on input/output analysis of the Portuguese pulp and paper sector. J. of Clnr. Prod, v. 330, 129851, 2022.

Del-Aguila-Arcentales, S., Alvarez-Risco, A., Jaramillo-Arévalo, M., De-la-Cruz-Diaz, M., Anderson-Seminario, M. M. Influence of Social, Environmental and Economic Sustainable Development Goals (SDGs) over Continuation of Entrepreneurship and Competitiveness. J. of Open Innovation Tech. Mark. and Complex, 8, 2-24, 2022.

Domingues, A. M., Souza, R. G., Luiz, J. V. R. Lifecycle social impacts of lithium-ion batteries: Consequences and future research agenda for a safe and just transition. Energy Research & Social Science, 118, 103756, 2024.

Finkbeiner, M., Schau, E. M., Lehmann, A., Traverso, M. Towards Life Cycle Sustainability Assessment. Sustain, 2, 3309-3322, 2010.

Giovanetti, J and Cleto, M. G. Impact of product certification in the Brazilian automotive batteries industry: a case study. Mgmt. Prod. São Carlos, v. 25, no. 2, p. 304-318, 2018.

Haddad, Y., Yuksek, Y. A., Jagtap, S., Jenkins, S., Pagone, E., Salonitis, K. Eco-social sustainability assessment of manufacturing systems: an LCA-based framework. Procedia CIRP, vol. 116, p. 312-317, 2023.

IEA. The battery industry has entered a new phase. 2025. Available at: < https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase>. Accessed in: 01 Jun. 2025.

International Organization for Standardization (ISO)., 2019. ISO 14040:2006 – Environmental management, life cycle assessment, principles and framework. Available at: <

https://www.iso.org/standard/37456.html>. Accessed in: 19 Apr. 2024.

HuntKey., 2024. The most comprehensive guide to battery life cycle. Available at: < https://www.huntkeyenergystorage.com/battery-life-cycle/>. Accessed in: 05 Dec. 2024.

Jayasanka, T. A. D. K., Darko, A., Edwards, D. J., Chan, A. P. C., Jalaei, F. Automating building environmental assessment: A systematic review and future research directions. Envr. Impact. Assmt. Rev, 106, 107465, 2024.

Kies, A. D., Krauß, J., Schmetz, A., Schmitt, R. H., Brecher, C. Interaction of Digital Twins in a Sustainable Battery Cell Production. Procedia, 107, 1216-1220, 2022.

Kokare, S., Oliveira, J. P., Godina, R. Life cycle assessment of additive manufacturing processes: A review. J. of Mfg. Sys, vol. 68, p. 536-559, 2023.

Kouloumpis, V., Konstantzos, G. E., Chroni, C., Abeliotis, K., Lasaridi, K. Does the circularity end justify the means? A life cycle assessment of preparing waste electrical and electronic equipment for reuse. Susble. Prod. Cons, 41, 291-304, 2023.

Larsen, V. G., Tollin, N., Sattrup. P. A., Birkved, M., Holmboe, T. What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. J. of Bldg. Eng, vol. 50, 104203, 2022.

Leal, V. M., Ribeiro, J. S., Coelho, E. L. D., Freitas, M. B. J. G. Recycling of spent lithium-ion batteries as a sustainable solution to obtain raw materials for different applications. J. of En. Chem, 79, 118-134, 2023.

Maisel, F., Neef, C., Marscheider-Weidemann, F., Nissen, N. F. A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles. Res, Conserv. & Recycl, 192, 106920, 2023.

Mármol, C., Martín-Mariscal, A., Picardo, A., Peralta, E. Social life cycle assessment for industrial product development: A comprehensive review and analysis. Heliyon, vol. 9, 22861, 2023.

McMahon, K., Mugge, R., Hultink, E. J. Overcoming barriers to circularity for internal ICT management in organizations: A change management approach. Res. Conserv. & Recycl, 205, 107568, 2024.

Minozzo, R., Minozzo, E. L., Deimling, L. I., Santos-Mello, R. Plumbemia in workers in the automotive battery recycling industry in Greater Porto Alegre, RS. BR. J. of Pathol. and Lab. Med, v. 44, n. 6, p. 407-412, 2008.

Nakhle, P., Stamos, I., Proietti, P., Siragusa, A. Environmental monitoring in European regions using the sustainable development goals (SDG) framework. Envi. and Sustain. Ind, 21, 100332, 2024.

Palomero, J. C., Freboeuf, L., Ciroth, A., Sonnemman, G. Integrating circularity into Life Cycle Assessment: Circularity with a life cycle perspective. Clnr. Envir. Sys, 12, 100175, 2024.

Pradhan, B. K., Yadav, S., Ghosh, J., Prashad, A. Achieving the Sustainable Development Goals (SDGs) in the Indian State of Odisha: Challenges and Opportunities. Wrd. Dev. Sustain, 3, 100078, 2023.

Rebolledo-Leiva, R., Moreira, M. T., González-García, S. Progress of social assessment in the framework of bioeconomy under a life cycle perspective. Renew. and Sustain. En. Rev, 175, 113162, 2023.

Rohkohl, E., Schönemann, M., Bodrov, Y., Herrmann, C. Multi-criteria and real-time control of continuous battery cell production steps using deep learning. Adv. Ind. and Mfg. Eng, 6, 100108, 2023.

Samani, P. Synergies and gaps between circularity assessment and Life Cycle Assessment (LCA). Sci. of the Tot. Environ, vol. 903, 166611, 2023.

Sazdovski, I., Batlle-Bayer, L., Bala, A., Margallo, M., Azarkamand, S., Aldaco, R., Fullana-i-Palmer, P. Comparative assessment of two circularity indicators for the case of reusable versus single-use secondary packages for fresh foods in Spain. Heliyon, 10, e27922, 2024.

Scheller, C., Kishita, Y., Blömeke, S., Thies, C., Schmidt, K., Mennenga, M., Herrmann, C., Spengler, T. S. Designing robust transformation toward a sustainable circular battery production. Procedia, 116, 408-413, 2023.

Shafiei, K., Zadeh, S. G., Hagh, M. T. Planning for a network system with renewable resources and battery energy storage, focused on enhancing resilience. J. of En. Stor, 87, 111339, 2024.

Shi, Y., Chen, X., Jiang, T., Jin, Q. Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials. Sustain. Prod. and Cons, 35, 525-538, 2023.

Skare, M., Gavurova, B., Kovac, V. Mitigating resource curse impact through implementing circular economy effective strategies. Res. Pol, 92, 104962, 2024.

Springer, S. K., Wulf, C., Zapp, P. Potential Social Impacts regarding working

conditions of Fuel Cell Electric Vehicles. Int. J. of H. En, 52, 618-632, 2024.

Tancin, R. J., Özdoğru, B., Dutta, N. S., Finegan, D, P., Villers, B. J. T. Direct reuse of graphite and lithium nickel manganese cobalt oxide (NMC) recovered from ultrafast-laser ablation debris in Li-ion battery electrodes. J. of Pwr. Sources, 596, 234027, 2024.

Toosi, H. A., Lavagna, M., Leonforte, F., Del Pero, C., Aste, N. A novel LCSA-Machine learning based optimization model for sustainable building design-A case study of energy storage systems. Bldg. and Environ, 209, 108656, 2022.

Tsalidis, G. A., Xevgenos, D., Ktori, R., Krishnan, A., Posada, J. A. Social life cycle assessment of a desalination and resource recovery plant on a remote island: Analysis of generic and site-specific perspectives. Sustain. Prod. and Cons, v. 37, 412-423, 2023.

Tulve, N. S., Geller, A. M., Hagerthey, S., Julius, S. H., Lavoie, E. T., Mazur, S. L., Paul, S. J., Frey, H. C. Challenges and opportunities for research supporting cumulative impact assessments at the United States environmental protection agency's office of research and development. The Lancet Regional Health – Americas, 30, 1-7, 2024.

United Nations. The 17 Goals. Available at: . Accessed in: 11 Apr. 2024.

Vogt, M and Herrmann, C. Energy efficiency of technical building services in production environments – Application to dry rooms in battery production. CIRP Annals – Manufacturing Technology, 70, 21-24, 2021.

US. Rsc. Conserv. & Recycl. 201, 107218. https://doi.org/10.1016/j.resconrec.2023.107218

Zakari, A., Khan, I., Tan, D., Alvarado, R., Dagar, V. Energy efficiency and sustainable development goals (SDGs). En, 239, 122365, 2022.

Zhou, H., Li, W., Poulet, T., Basarir, H., Karrech, A. Life cycle assessment of recycling lithium-ion battery related mineral processing by-products: A review. Minerals Eng, 208, 108600, 2024.

Author's Affiliation

Ferreira, E.M. - Professor at Vietnamese-German University, Bình Dương, Vietnam.

Authors' Contribution

Ferreira, E.M. - The author is responsible for the design of the research, data collection and analysis, writing of the text and all steps involved in publishing the manuscript.

MERCATOR

ARTICLE

Editors in Charge

Alexandra Maria Oliveira
Alexandre Queiroz Pereira