Research paper
6th PLATE 2025 Conference
Aalborg, Denmark, 2-4 July 2025

Assessing socio-economic impacts of Lithium-Ion Battery recycling through Multi-Regional Input-Output Analysis

Pascal Goeppel[a], Julius Ott[a,b], Martina Zimek[a], Rupert J. Baumgartner [a,b]
a) Department of Environmental Systems Sciences, University of Graz, 8010 Graz, Austria
b) Christian Doppler Laboratory for Sustainable Product Management Enabling a Circular Economy, 8010 Graz, Austria

Keywords: Lithium-ion batteries (LIB); Multi-Regional Input-Output analysis (MRIO); Recycling; End of Life (EoL); Socio-economic impacts.

Abstract: The expected rise in electromobility and the increasing use of lithium-ion batteries (LIBs) is generating new challenges and opportunities, particularly in the End-of-Life (EoL) management of batteries. One of these challenges are the socio-economic impacts associated with the EoL process steps on which this paper focuses on. With the method of Multi-Regional Input-Output (MRIO) analysis, a selected recycling process route in Europe is assessed regarding socio-economic impacts, first at current demand (baseline scenario) and followed by an upscaled demand. The results provide insight into differences in some socio-economic impact categories, such as employment, vulnerable employment, and worker remuneration. The scale-up scenarios show, among other things, an increase in the workforce and remuneration (positive impact). However, with an increase in vulnerable employment, negative socio-economic impacts are also evident in Europe-centered recycling processes. The results furthermore show that changing recycling processes can lead to sustainability trade-offs. Due to the limited number of indicators in the selected method, it is not possible to provide an overall picture of social impacts. However, this research shows a clear change in the individual impacts, which underlines the need for proactive measures to overcome infrastructure problems, expand recycling capacities, and improve employment conditions in all sectors.

Introduction

The transport sector is one of the main sources of greenhouse gas emissions. Road traffic, particularly vehicles, generates the most emissions in the transport sector. To reduce traffic-related emissions, electric vehicles powered by LIBs are a promising alternative to conventional vehicles with combustion engines. Such a substitution of conventional vehicles by electric vehicles leads to an expected increase in demand for LIBs. The forecast for the rising demand for LIBs depends on the scenario, but a tenfold increase until 2030 seems realistic (Usai et al, 2022). It is also predicted that future demand for lithium for LIBs in electric vehicles will exceed current raw material production in 2040 (Maisel et al, 2023).
The challenges in the life cycle of batteries, such as the scarcity of raw materials and the generation of waste, require effective EoL management strategies, such as effective recycling technologies. There are still substantial challenges in the EoL management of LIBs. The emergence of potential sustainability trade-offs underlines the challenges in LIB recycling processes. Sustainability trade-offs refer to the complex and often interrelated decisions that are made in the pursuit of sustainable outcomes, where improvements in one area may come at the expense of another (Morrison-Saunders & Pope, 2013). New Europe-centered recycling processes can improve the economic situation in certain countries (e.g., increasing employment). However, this could also lead to negative effects in countries currently involved in the EoL processes of LIBs. The use of labour-related indicators (e.g., through an MRIO analysis) can be a promising approach to analyzing sustainability trade-offs and the associated impacts (Zimek et al, 2022).
The ecological impacts of LIBs recycling are being increasingly addressed in scientific research (Meshram et al, 2020; Costa et al, 2021). The industry is likewise showing an increasing interest in reducing its environmental

impact (notably through the EU Battery Regulation [1] with mandatory raw material-dependent recycling quotas, which are to be implemented by 2030 and 2035). However, although research in LIB recycling is increasing, socio-economic impacts are often neglected, although the recycling of LIBs entails several socio-economic impacts that need to be identified and consequently avoided (see for example, Yıldızbaşı et al, 2022 or Koese et al, 2023).

This can be explained, for example, by the fact that there are no common and generally accepted methods for assessing the socio-economic impacts, especially of emerging technologies (Sanchez et al, 2021; Cecere et al, 2024) Socio-economic assessments differ considerably from environmental assessments as they focus on a broader range of qualitative and quantitative data, complex feedback loops and different stakeholder interests. This complexity makes standardization and consensus on assessment methods difficult (Ramos, 2024; Rebolledo-Leiva et al, 2023). Despite these challenges, it is increasingly recognized that socio-economic impacts need to be integrated into assessment methods, as they are essential for comprehensively evaluating the holistic impacts of technologies. The importance of assessing the socio-economic impacts of emerging technologies, such as new LIB recycling processes, is of particular relevance, as the structures in the recycling processes, the countries involved, and consequently, the social context can change.

Therefore, the research aim of this paper is to identify the socio-economic impacts of LIB recycling processes with a focus on a Europe-centered value chain (as part of the FREE4LIB[2] project). More precisely the aim is to answer the following research questions.

(1) What are the direct impacts of the lithium-ion battery recycling process for six socio-economic indicators throughout the phases of collection, pre-treatment, metal recovery, and assembly in different European countries?
(2) How do these impacts differ under scale-up scenarios driven by the increasing demand for batteries in the electric vehicle sector?

Methods

Depending on the field of application, different methods exist to assess socio-economic impacts. For the common field of application, the evaluation of (public) investments, tools like social return on investment or cost-benefit analysis are used (Cerioni et al, 2021). For the evaluation of value chains, life cycle assessment (e.g., with the help of the Social Hotspots Database) or MRIO analysis are often used (Zimek et al, 2022).

While life cycle assessment approaches are usually product or site-specific, MRIO follows a top-down approach. It is a quantitative approach which allows for an in-depth analysis. MRIO is a method used to assess the interregional flows of goods and services by linking the economic activities of multiple regions through their trade relationships (Wiedmann et al, 2011). Furthermore, socio-economic impacts often vary greatly depending on the region (country). Therefore, MRIO analysis is a well-suited method to account for potential regional disparities by tracking indirect effects along supply chains at the sectoral level (Miller and Blair, 2009). Several MRIO databases exist. For this research, the freely accessible database EXIOBASE v3.8 is used, with data from the year 2016, the most recent available data at the time when the research was done (Stadler et al, 2018).

This study follows a three-step approach, including:

(1) The preparation step: set up of a representative product system for the battery recycling, and selection of impact categories,
(2) The baseline calculation: calculation of the socio-economic impacts based on the default final demand, and
(3) The scale-up calculation: calculation of the socio-economic impacts in dependence on increasing battery recycling volumes.

First step: Preparation

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02006L0066-20180704

[2] FREE4LIB is an EU-funded research project on 21 technologies with the aim to develop new technologies (5-6 TRL) to achieve sustainable and efficient processes to recycle EOL LIBs, Source: https://www.freeforlib.eu/.

A product system of four phases is selected based on a literature review and information from the Horizon Europe project FREE4LIB. The process under study starts with the collection of EoL LIBs in Spain. This is followed by the pre-treatment in France and then the actual recycling, in this study through metal recovery, in Belgium. The final phase is the production and assembly of new LIBs in the Republic of Türkye. Next, due to the limited availability of sectors in the used EXIOBASE v3.8 database, each process step is matched with a representative related sector in the database (see Table 1 below).

Phase	**Country**	**Sector in EXIOBASE v3.8**
Phase 1: Collection	Spain	Other land transport
Phase 2: Pre-Treatment	France	Waste water treatment, other
Phase 3: Metal Recovery	Belgium	Re-processing of secondary precious metals
Phase 4: Assembly	Republic of Türkiye	Manufacture of electrical machinery and apparatus n.e.c.

Table 1. Phases included in MRIO analysis of LIB recycling showing country and respective sector in EXIOBASE v3.8

The next step in the preparation phase is the selection of socio-economic impact categories. The EXIOBASE v3.8 database used offers six socio-economic impact categories, all of which are used as impact categories in this study (see Table 2 below). The six socio-economic impact categories include:

- Employment: aggregated number of individuals involved in productive activities.
- Employment hours: total hours worked by all individuals together in one year.
- Value added: economic value created through the production of goods and services by subtracting the value of intermediate consumption.
- Compensation of employees: all forms of remuneration aggregated, including both cash and non-cash benefits.
- Vulnerable employment: aggregated number of individuals who work under difficult conditions, e.g., no formal employment contracts and no social protection.
- Vulnerable employment hours: total hours worked under vulnerable working conditions in one year.

High numbers as results for the different impact categories are sometimes interpreted as positive and sometimes interpreted as negative. For example, employment should be increased, so a high number is perceived as positive and vulnerable employment should be decreased, so a high number is perceived as negative. This is expressed by the term “high value perception”. Table 2 below shows the units of each impact category and the high value perception.

Socio-economic impact category	**Unit**	**High value perception**
Employment	in 1,000 persons (1000 p)	positive
Employment hours	hours (hrs)	positive
Value added	in millions of euros (M.EUR)	positive
Compensation of employees	in millions of euros (M.EUR)	positive
Vulnerable employment	in 1,000 persons (1000 p)	negative
Vulnerable employment hours	hours (hrs)	negative

Table 2. EXIOBASE v3.8 socio-economic impact categories.

Second step: Baseline calculation

The calculation of the baseline impacts consists of a filtering of the database by the selected sectors and regions. The obtained values for employment and vulnerable employment and employment hours and vulnerable employment hours are put into relation to calculate vulnerability ratios. Further, the results of the baseline calculation can be used to provide an idea of the overall direct impacts of the product system in the selected sector and region. Lastly, the results are used as a benchmark for the scale-up scenarios.

Third step: Scale-up calculation

To simulate the consequences of the expected demand growth of LIBs in the following years, the final demand in the selected sectors and regions (see Table 1) is increased by factor 10. Then the whole system is updated to the new final demand and the impacts are filtered in a similar manner as in the baseline calculation. For the relative change to the baseline in percent (as displayed in Figure 2) the results are divided by the baseline impacts.

Results

Like the methods section, the results separately contribute to answering the two different research questions regarding baseline and scale-up scenario. While the analysis of the baseline focuses on the differences in impacts between the phases, the scale-up results look at the differences both within and between the phases

Baseline scenario

In the baseline scenario, phase 1 (collection) and phase 4 (assembly) exhibit notably high absolute values for all impact categories. Compared to phase 3 (metal recovery) which has low values for all impact categories, the values differ by several orders of magnitude. Phase 2 (pre-treatment) is somewhere in between. This result can be observed for all impact categories. Exemplary, here are the values for employment (in 1000 persons, see table 2):

- Phase 1 Collection: 258 000
- Phase 2 Pre-treatment: 6 760
- Phase 3 Metal recovery: 0.00273
- Phase 4 Assembly: 360 000

In comparison, the vulnerability ratio is rather balanced, with all results in the same order of magnitude. Figure 1 below shows the ratio of vulnerability for the different phases.

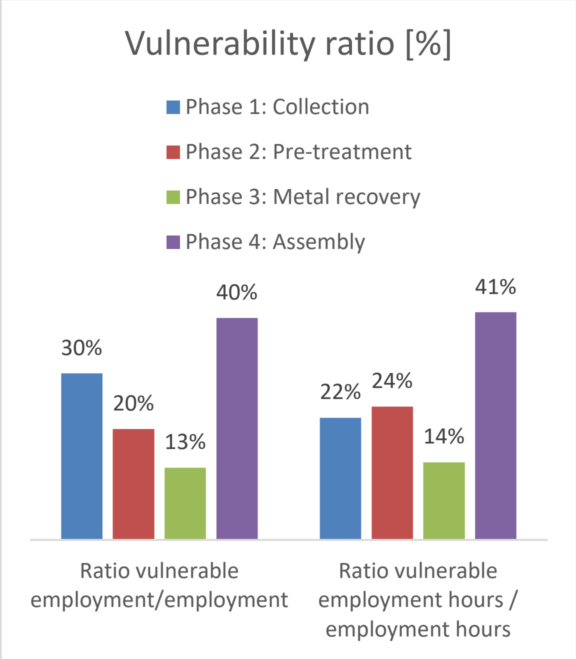

Figure 1. Relative vulnerability of different phases

A low vulnerability ratio represents a low share of vulnerable employment of the total employment. For both the employment ratio and the employment hour ratio, phase 3 (metal recovery) has the lowest value, while phase 4 (assembly) has the highest value. However, phase 1 stands out with a lower ratio when looking at employment hours compared to the number of employees ratio. Phase 4 has a very high share of vulnerability in both the number of employees and employment hours.

Scale-up scenario

Figure 2 below shows the results of the scale-up scenario for the six socio-economic impact categories in the four phases.

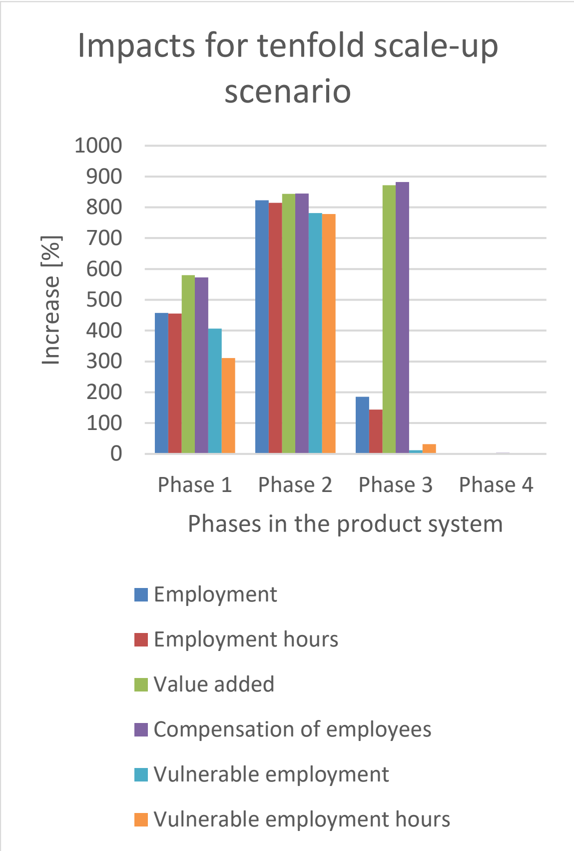

Figure 2. Comparative overview of the scaled-up impacts

The first observation is the increased impact in all phases and sectors through the scale-up of the demand. The increasing demand for LIBs leads to increased employment, compensation, and added value. However, this also results in an increase in the amount of vulnerable employment, particularly in phase 1 (collection) and phase 2 (pre-treatment). Interestingly, the impact of the different phases does not grow equally. A tenfold increase in the demand does not lead to a tenfold increase in the impacts. For example, while the compensation of employees grows by 573% for phase 1 (collection), phase 2 (pre-treatment), and phase 3 (metal recovery) increase between factors 8 and 9. Phase 4 (assembly) almost stays the same as in the baseline scenario. Therefore, the impact in the different phases increases at a different rate. However, the ratio of the different impact categories within one phase does not change ("linear combination" of the baseline, not observable in figure 2). A final observation is the minimal increase of the impacts in phase 4 (assembly), despite the relatively high impacts in the baseline scenario.

Discussion

The results of this study show that the socio-economic impacts of Europe-centered recycling of LIBs are rather complex. In most results, the impact categories with a positive high-value perception and a negative high-value perception (see table 2) show similar behavior (i.e., either both are high or both are low). This means that, in this case, the Europe-centered recycling of LIBs creates jobs, increases remuneration, but also leads to socio-economic trade-offs. These trade-offs include vulnerable employment and vulnerable employment hours, as in this research, but can also encompass other impact categories not included here.
Apart from the "local" trade-offs analyzed in this research, other countries and sectors may also be affected. Changes in processes, such as the introduction of new LIB recycling technologies and the substitution of economic activities, could lead to shifts in activity and therefore impact in other countries and sectors as well. For example, an increase in employment in one country and sector might result in a decrease in employment in other countries and sectors. The extent to which changes in the economic system are associated with socio-economic effects in other countries requires further analysis.
Regarding the scale-up scenarios, the results give an insight into potential future socio-economic challenges. In contrast to intuitive expectations, the impacts do not rise equally with the increased demand. The impacts of the different phases even increase at different rates which changes the priority of the different phases, to be addressed with policy measures, compared to the baseline scenario.

Possible reasons for the variance in the impact growth could be diverse, such as:

- different share of employment in the sectors, e.g., especially the assembly phase is characterized by a high number of employees and hours worked,
- the same growth in absolute values of sectors that already have a high baseline impact is less in relative values, and
- the overlap of direct effects (higher demand) and indirect effects (substitution with other products), e.g., while the manufacturing of electric vehicles rises, the manufacturing of conventional vehicles

decreases. This affects some sectors more than others.

The results align with findings from existing literature. As previously noted by Fleischmann et al. (2023), the notion that recycling can be financially beneficial is supported. Further, the finding from Zimek et al. (2022), that an increase in demand is projected to generate additional job opportunities is also supported.
Major policy implications arise for mitigating the negative socio-economic impacts associated with recycling LIBs. Policy recommendations should address the identified weaknesses, focusing on strengthening job security, improving the quality of employment, and mitigating potential negative socio-economic impacts. In addition, policymakers must recognize the broader impacts that go beyond the local context examined in this study. Shifts in economic activity resulting from changes in the recycling of LIBs can have cross-country and cross-sectoral impacts and require comprehensive policy measures to manage and mitigate unintended consequences. To this end, the development of collaborative strategies and mechanisms for information sharing and coordination between relevant stakeholders and authorities in different regions is important to address potential co-benefits and ensure a more coherent and effective approach to reduce negative socio-economic impacts.
The insights gained from the scale-up scenarios highlight potential future socio-economic challenges that require proactive policy measures. The observed difference in impact growth highlights the need for adaptive policy measures that can respond effectively to the changing landscape of LIB recycling, considering factors such as the distribution of employment, relative impact growth and the interplay of direct and indirect effects.

Limitations
One limitation of using MRIO is that the databases include rather limited recent data (such as from 2016 in this study). Other limitations are the country-specific factors that strongly influence the results, such as lower wages in the Republic of Türkyie versus higher wages in France and Spain. The product system is very specific, and the data availability is limited (rather new technology), especially for the metal recovery phase.

Conclusions
This research contributes to the knowledge gap of socio-economic impacts in the LIB EoL. While the baseline analysis helps to identify sensitive areas such as vulnerable employment in the assembly phase, the scale-up indicates that the growing demand for LIBs causes a substantial socio-economic transformation that should be anticipated. However, this transformation cannot be simply extrapolated from the status quo but can lead to surprising shifts in the areas of concern. Future research aims at modifying product systems by integrating more details and assessing the sensitivity of the results.

Acknowledgments
This research was funded by the European Commission as part of the Horizon Europe project FREE4LIB, and we declare no conflicts of interest. Furthermore, without previous research at UNI Graz and the Christian Doppler Laboratory for Sustainable Product Management enabling a Circular Economy, the present research would have been much more challenging to conduct.

References
Cecere, G, Hassan, R., Eltohamy, H. & Rigamonti, L. (2024). A socio-economic assessment of an emerging technology in the mining industry. The International Journal of Life Cycle Assessment, https://doi.org/10.1007/s11367-024-02392-w.
Cerioni, E., & Marasca, S. (2021). The methods of social impact assessment: The state of the art and limits of application. Calitatea, 22(183), 29–36.
Costa, C.M., Barbosa, J.C., Goncalves, R., Castro, H., Del Campo, F.J., LancerosMendez, S., Recycling and environmental issues of lithium-ion batteries: advances, challenges and opportunities, Energy Stor. Mater. 37 (2021) 433–465. https://doi.org/10.1016/j.ensm.2021.02.032
Fleischmann, J., Hanicke, M., Horetsky, E., Ibrahim, D., Jautelat, S., Linder, M., Schaufuss, P., Torscht, L., & van de Rijt, A. (2023). Battery 2030: Resilient, sustainable, and circular. McKinsey & Company, 2–18.
Koese, M., Blanco, C.F., Vert, V.B. & Vijver, M.G. (2023). A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage. Journal of

Industrial Ecology, 27(1), pp. 223-237. DOI: 10.1111/jiec.13347

Maisel, F., Neef, C., Marscheider-Weidemann, F. & Nissen, N.F. (2023). A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles. Resources, Conservation and Recycling, 192, 106920. https://doi.org/10.1016/j.resconrec.2023.106920

Meshram P, Mishra A, Abhilash Sahu R. Environmental impact of spent lithium ion batteries and green recycling perspectives by organic acids - a review. Chemosphere 2020;242:125291.

Miller, R.E. & Blair, P.D. (2009). Input-output analysis: Foundations and Extensions, Second ed., Cambridge Univ. Press, Cambridge. https://doi.org/10.1017/CBO9780511626982

Morrison-Saunders, A. & Pope, J. (2013). Conceptualising and managing trade-offs in sustainability assessment. Environmental Impact Assessment Review, 38, pp. 54-63. https://doi.org/10.1016/j.eiar.2012.06.003

Ramos, A. (2024). Sustainability assessment in waste management: An exploratory study of the social perspective in waste-to-energy cases. Journal of Cleaner Production, 475, 143693. https://doi.org/10.1016/j.jclepro.2024.143693

Rebolledo-Leiva, r., Moreira, M.T. & González-García, S. (2023). Progress of social assessment in the framework of bioeconomy under a life cycle perspective. Renewable and Sustainable Energy Reviews, 175, 113162. DOI: 10.1016/j.rser.2023.113162

Sanchez, M., Sanz, S., & Ventosa, P. (2021). Review of economic and socio-economic studies on recycling topics. ENT Environment and Management for the European Commission, DG JRC, under contract number B.B651793.

Stadler K, R. Wood, T. Bulavskaya, C.J. Sodersten, M. Simas, S. Schmidt, A. Usubiaga, J. Acosta-Fernandez, J. Kuenen, M. Bruckner, S. Giljum, S. Lutter, S. Merciai, J.H. Schmidt, M.C. Theurl, C. Plutzar, T. Kastner, M. Eisenmenger, K. Erb, A. de Koning, A. Tukker (2018) EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables, Journal of Industrial Ecology 22(3)502-515. doi: 10.1111/jiec.12715

Usai, L. et al 2022 Environ. Res.: Infrastruct. Sustain. 2 011002. doi : https://doi.org/10.1088/2634-4505/ac49a0

Wiedmann, T., Wilting, H.C., Lenzen, M., Lutter, S. & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input-output analysis, Ecological Economics, 70, pp. 1937-1945.

Yıldızbaşı, A., Öztürk, C., Yılmaz, İ. & Arıöz, Y. (2022). Key Challenges of Lithium-Ion Battery Recycling Process in Circular Economy Environment: Pythagorean Fuzzy AHP Approach. Lecture Notes in Networks and Systems, 308, pp. 561-568. DOI: 10.1007/978-3-030-85577-2_66

Zimek, M., Asada, R., Baumgartner, R.J., Brenner-Fliesser, M., Kaltenegger, I., & Hadler, M. (2022). Sustainability trade-offs in the steel industry – A MRIO-based social impact assessment of bio-economy innovations in a belgian steel mill. Cleaner Production Letters, 3, 100011. https://doi.org/10.1016/j.clpl.2022.100011