CEST 2023

18th International Conference on Environmental Science and Technology

Athens, Greece, 30 August to 2 September 2023

Comparative life cycle assessment of lithium-ion batteries

TOURNAVITI M.[1], SAVVA C. [1], VLACHOKOSTAS C. [1, *]

[1] Dept. of Mechanical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

*corresponding author:
e-mail: vlahoco@meng.auth.gr

Abstract: The transportation sector is the second largest source of carbon emissions worldwide. In the process of achieving zero emissions, the electrification of the sector and the replacement of internal combustion engine vehicles (ICEVs) with electric vehicles (EVs) is being promoted. Batteries as the main component of EVs contribute significantly to their environmental impact along their life cycle. The high energy demand for battery production leads to higher carbon emissions to produce EVs than ICEVs. Additionally, during the charging of the batteries, the carbon emissions are directly linked to the carbon intensity of the electricity mix used. Currently, lithium-ion batteries (LIBs) are widely used as energy sources for EVs. This paper presents a comparative life cycle assessment (LCA) of three types of LIBs: lithium-ion phosphate, lithium manganese oxide, and lithium nickel manganese cobalt oxide. The environmental impact of the entire life cycle of the batteries, from the extraction of raw materials to end-of-life (EoL) management, was assessed. The results were then compared for the three battery types. The influence of the electricity mix used to charge the batteries was also assessed, by applying a different scenario of electricity mix for power generation than the base case.

Keywords: life cycle assessment; environmental impacts; electric vehicles; lithium-ion batteries

Abbreviation	Definition
EV	Electric Vehicles
EoL	End-of-Life
GWP	Global Warming Potential
HCT	Human Carcinogenic Toxicity
HNCT	Human Non-Carcinogenic Toxicity
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFP	Lithium iron phosphate
LIB	Lithium-Ion Battery
LMO	Lithium manganese oxide
MRS	Mineral Resource Scarcity
NCA	Lithium nickel cobalt aluminum oxide
NCM	Lithium nickel cobalt manganese oxide

1. Introduction

The ongoing efforts to decarbonize energy production have created the need for energy storage. Currently, LIBs have become one of the main energy storage solutions. Their remarkable properties, such as high energy density, high power density, long life cycle, low self-discharge rate, and lack of memory effect make them suitable for a wide range of applications. This fact has led to the rapid development of their technology, especially for emerging applications such as EVs. In EVs, the demand for more efficient battery packs grows continuously. The substitution of fossil fuels with renewable energy sources provided by electricity as energy carriers can significantly reduce CO_2 emissions in the automotive sector (Vlachokostas, 2022).

Different LIBs are made of variable materials that affect their efficiency, their properties, and the impact they have on the environment. The main components of a LIB are the cathode, electrolyte, and separator. The cathode is the part whose composition and specific capacity strongly affect the performance of the battery. The most used cathode materials are lithium iron phosphate (LFP), lithium nickel cobalt manganese oxide (NCM), lithium manganese oxide (LMO), and nickel cobalt aluminum oxide (NCA). LFP and LMO are mature technologies, the safest among the other LIBs, and they do not contain toxic or hazardous metals. Cathodes containing cobalt (NCM & NCA) are the most promising candidates for EV applications due to their energy density, reliability, and durability (Zubi et al., 2018).

Although LIBs are a promising solution for energy storage, many issues have emerged. Firstly, critical elements, such as cobalt, nickel, and potentially lithium that are necessary for the production of LIBs are limited and unevenly distributed. Secondly, large-scale battery production will cause the massive exploitation of natural resources including energy and water. In addition, the manufacturing and assembly of LIBs require large amounts of energy. Lastly, the safe and with minimal environmental burden disposal of EoL batteries has become a concerning issue. Therefore, their sustainability should be assessed throughout their life cycle starting from raw material extraction to their manufacturing, supply, transportation, use and finally recycling and waste management (Harper et al., 2019). For this purpose, LCA for LIBs is attracting

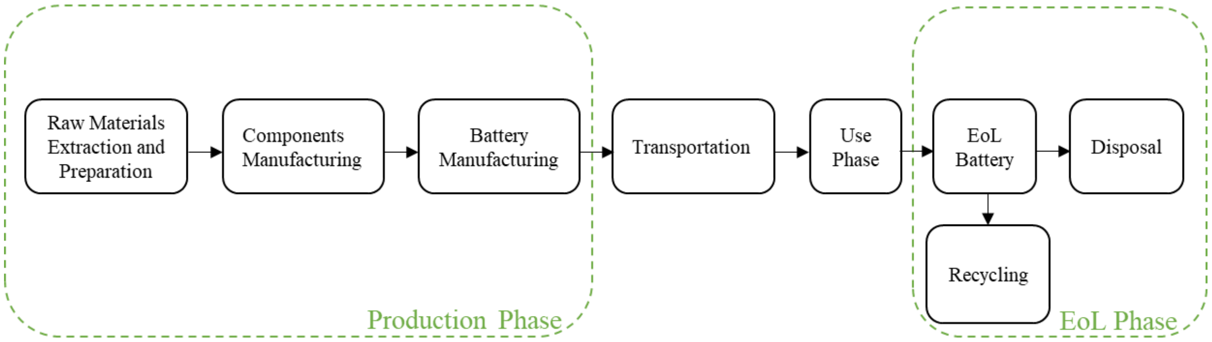

Figure 1: System Boundary of LCA for LIBs

more and more attention. LCA provides an evaluation of a product or service's inputs, outputs, and potential environmental impacts during the life cycle by quantifying materials, energy consumption, and emissions to the environment (McManus, 2012). The present study aims to assess and compare the environmental impacts of three different types of LIBs. The three battery types assessed are LFP, NCM, and LMO.

2. Methodology

LCA was conducted according to the ISO 14040 standards. A cradle-to-grave analysis was conducted, including the phases of production, transportation, use, and EoL as shown in Fig. 1. Extraction and preparation of raw materials wasn't considered as an individual phase, but it's included in the battery's production phase. The functional unit of each LIB system was defined as the amount of energy of 1 GJ delivered by LIBs.

Table 1. Production and EoL phase data sources

Battery Type	Production phase	EoL phase
LFP	Majeau-Bettez et al. (2011)	Jiang et al. (2022)
NCM	Notter et al. (2010)	Fisher et al. (2006)
LMO	Ellingsen et al. (2014)	Jiang et al. (2022)

The life cycle inventory (LCI) was based on both literature and own assumptions. Inventory for the production and EoL phases was based on literature data. In Table 1, data sources for production and EoL phase for each LIB are presented. Production of LIBs was assumed to take place in Yibin city of China, from where LIBs are transported by freight lorry to Shanghai. From Shanghai, LIBs are transported by sea bulk carrier to Rotterdam and from there via freight lorry to Thessaloniki. The total distance covered by freight lorry and sea bulk carrier was estimated at 4,282 km and 22,222 km respectively. Background data were provided by the Ecoinvent database (Ecoinvent, 2021).

For the use phase, it was assumed that the efficiency of LIBs is 90% and the capacity reached at 80% of the nominal capacity according to literature data. In Table 2, the data source for the specific energy and the number of life cycles of each LIB are presented. The required amount of mass to deliver the desired amount of 1 GJ of energy was calculated based on specific energy, number of life cycles, and capacity and are presented in Table 2 as well. It was assumed that the electricity used to charge the LIBs is produced with the 2021 electricity mix of Greece (Renewable Energy Sources Operator And Guarantees of Origin, 2023). Finally, it was assumed that hydrometallurgy is the treatment that takes place in the EoL phase. With the hydrometallurgy process, recovery of lithium, copper, and aluminum from all types of LIBs is possible, as well as manganese from LMO and NCM batteries and cobalt and nickel from NCM batteries.

Table 2. LIBs properties

Battery Type	Specific energy [Wh/kg]	Life Cycles	Source	Required mass [kg]
LFP	110	4000	Ioakimidis et al. (2019)	0.789
LMO	120	1250	Zubi et al. (2018)	2.3148
NCM	149.2	2600	Ellingsen et al. (2014)	0.895

LCA was carried out using the openLCA software. Recipe 2016 Midpoint (H) characterization method (Huijbregts et al., 2017) was selected for the impact assessment. Global warming potential (GWP), human carcinogenic toxicity (HCT), non-carcinogenic toxicity (HNCT), as well as mineral resource scarcity (MRS), were the selected impact categories.

3. Results

3.1. Comparative results

In Fig.2, a comparative assessment of the impact caused by LIBs in the selected categories is presented.

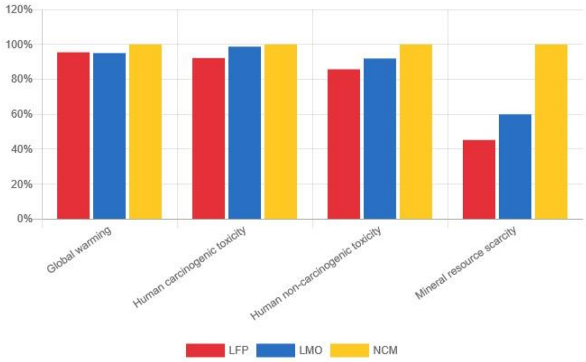

Figure 2: Comparative results of LCA

In Figs. 3-5 contribution from each phase of the life cycle of LIBs for the selected impact categories is shown.

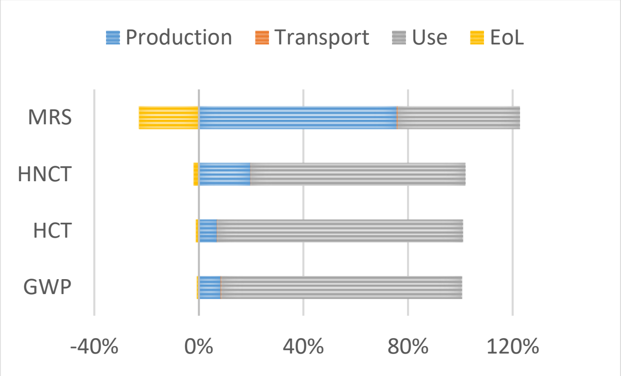

Figure 3: Contribution of each stage to environmental impacts-LFP

NCM batteries have the highest impact on GWP while LMO batteries have the lowest, reduced by 4.98% compared to NCM. LFP batteries have a lower impact compared to NCM, reduced by 4.56%. NCM batteries have the highest impact on GWP due to the higher required amount of energy for the production and EoL phase. As shown in Figs. 3-5, the use phase has the highest contribution on GWP for all the types of LIBs.

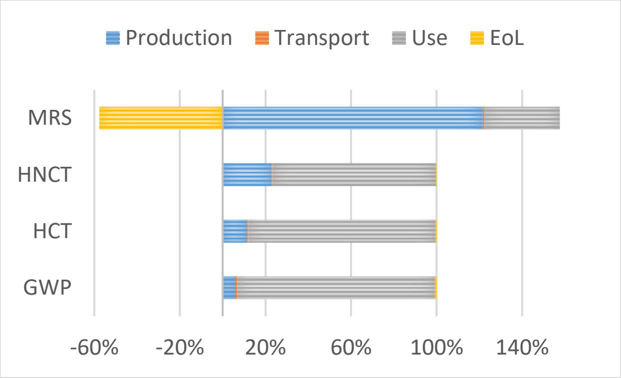

Figure 4: Contribution of each stage to environmental impacts-NCM

NCM batteries have the highest impact on both HCT and HNCT, while LFP batteries have the lowest impact on those categories, reduced by 7.86% and 14.3% respectively compared to NCM. LMO batteries have a lower impact compared to NCM, reduced by 1.34% and 8.08% respectively. Finally, NCM batteries have the highest impact on MRS. LFP and LMO batteries have a lower impact compared to NCM, reduced by 14.29% and 8.08% respectively. NCM have the highest impact on HCT, HNCT, and MRS mainly due to their cobalt and nickel content, while LMO have a higher impact than LFP due to their manganese content.

As shown in Figs. 3-5, the use phase of LIBs contributes the most to the impact categories of HCT and HNCT, while the production phase has the biggest contribution to MRS. In the impact category of MRS, the significance of metals recovery is shown. Due to the metal recovered by the hydrometallurgy process at the EoL of LIBs, the total impact on MRS is reduced.

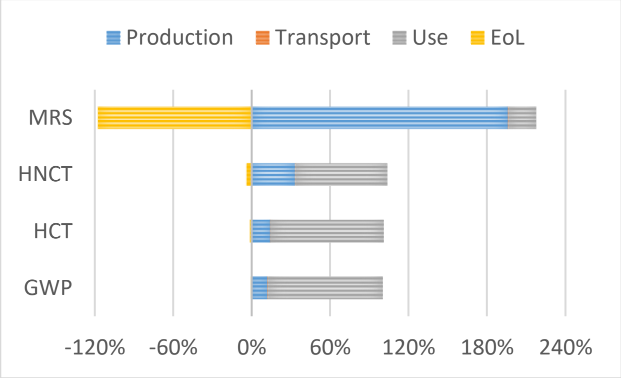

Figure 5: Contribution of each stage to environmental impacts-LMO

As shown in Figs. 3-5, the use phase of LIBs contributes the most to the impact categories of HCT and HNCT, while the production phase has the biggest contribution to MRS. In the impact category of MRS, the significance of metals recovery is shown. Due to the metal recovered by the hydrometallurgy process at the EoL of LIBs, the total impact on MRS is reduced.

3.2. Sensitivity analysis

Sensitivity analysis was conducted to evaluate the effect of the electricity mix used to charge LIBs, on the impact potential caused by the whole life cycle of LIBs, since the use phase is the biggest contributor to most of the impact categories. As an alternative, it was assumed that electricity is being produced with the average European mix, which is less carbon-intense than the Greek (Statista Research Department, 2023). It was assumed that the average European mix was produced in Greece. In Ecoinvent, there isn’t the choice of energy production from some specific electricity sources (e.g., nuclear) in Greece. In that case, the process chosen is the one referred to as the “Rest of the world”.

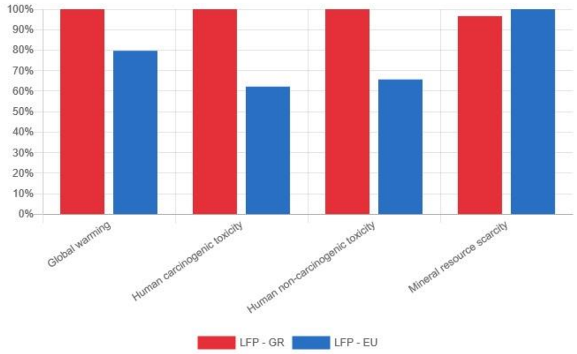

Figure 6: Comparative results for Greek and European electricity mix

In Fig.6, the comparative assessment between LFP batteries being charged by the average Greek and the average European mix is presented. The use of an alternative electricity mix has a similar effect on NCM and LMO batteries as well as LFP batteries. In the scenario in which LFP batteries are charged by the average European electricity mix, the impact on GWP, HCT, and HNCT is lower than the scenario in which they are charged by the average Greek electricity mix, by 20.28%, 37.73%, and

34.26% respectively. However, the impact on MRS is higher than the basic scenario, due to the impact caused by using nuclear energy.

4. Conclusions

A comparative environmental LCA of LFP, NCM, and LMO batteries was carried out considering their whole life cycle. The influence of the electricity mix used for battery charging was also assessed. In total, the NCM batteries had the highest impact on all categories. The LFP and LMO batteries had similar performance in most categories, in spite of the fact that the LFP battery endures more cycles than the LMO battery. During the production phase, the NCM battery caused the highest environmental burden and the LMO the lowest. The phase that contributes the most to all impact categories apart from MRS is the use phase. During the use phase, NCM contributed less to all impact categories. The hydrometallurgy recycling led to the reduction of the impact on MRS for all battery types due to the recovery of mineral elements. The transition to a less carbon-intense energy mix than the Greek led to the total reduction of the impacts caused during the use phase. Nonetheless, the use phase remains the one with the highest environmental burden. The only category for which an improvement wasn't observed after choosing a less carbon-intense energy mix was the MRS due to minerals used for nuclear energy production.

References

Ecoinvent (2021), The Life Cycle Inventory Data Version 3.8.

Ellingsen L., Majeau-Bettez G., Singh B., Srivastava A., Valøen L. and Strømman A. (2014), Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack, *Journal of Industrial Ecology*, **18**, 113-114.

Fischer K., Wallen E., Laenen P. and Collins M. (2006), Battery Waste Management Life Cycle Assessment, Environmental Resources Management

Harper G., Sommerville R., Kendrick E., Driscoll L., Slater P., Stolkin R., Walton A., Christensen P., Heidrich O., Lambert S., Abbott A., Ryder K., Gaines L. and Paul Anderson P. (2019), Recycling lithium-ion batteries from electric vehicles, *Nature*, **575**, 75–86.

Huijbregts M.A.J., Steinmann Z.J.N., Elshout P.M.F., Stam G., Verones F., Vieira M., Zijp M., Hollander A. and van Zelm R. (2017), Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, *The International Journal of Life Cycle Assessment*, **22**, 138-147.

Ioakimidis C.S., Murillo-Marrodán A., Bagheri A., Thomas D., Genikomsakis K.N. (2019), Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios, *Sustainability*, **11(9)**, 2527.

Jiang S., Hua H., Zhang L., Liu X., Wu H. and Yuan Z. (2022), Environmental impacts of hydrometallurgical recycling and reusing for manufacturing of lithium-ion traction batteries in China, *Science of the Total Environment*, **811**, 152224.

Majeau-Bettez G., Hawkins T. and Stromman A. (2011), Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles, *Environmental Science and Technology*, **45**, 4548–4554.

McManus M.C. (2012), Environmental consequences of the use of batteries in low carbon systems: The impact of battery production, *Applied Energy*, **93**, 288-295.

Notter D., Gauch M., Widmer R., Wager P., Stamp P., Zah R. and Althaus H. (2010), Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles, *Environmental Science and Technology*, **44**, 6550-6556.

Renewable Energy Sources Operator And Guarantees of Origin (2022), Residual Energy Mix 2021.

Statista Research Department (2023), Power production in the European Union (EU) 2021, by fuel, Statista, URL: https://www.statista.com/statistics/800217/eu-power-production-by-fuel/, Last visited: January 2023.

Vlachokostas Ch. (2022), Αειφορική Διαχείριση και Κυκλική Οικονομία [Sustainability Management and Circular Economy] (1st ed.), Yahoudis Publications.

Zubi G., Dufo-Lopez R., Carvalho M. and Pasaoglu G. (2018), The lithium-ion battery: State of the art and future perspectives, *Renewable Energy and Sustainable Energy Reviews*, **89**, 292-308.