POLITECNICO DI TORINO
Repository ISTITUZIONALE

A Study on the Cradle-to-Gate Environmental Impacts of Automotive Lithium-ion Batteries

Original
A Study on the Cradle-to-Gate Environmental Impacts of Automotive Lithium-ion Batteries / Accardo, A., Dotelli, G., Spessa, E.. - 122:(2024), pp. 1077-1082. (31st CIRP Conference on Life Cycle Engineering (LCE 2024) Turin (Italy) JUNE, 19-21 2024) [10.1016/j.procir.2024.02.037].

Availability:
This version is available at: 11583/2992208 since: 2024-09-04T10:21:56Z

Publisher:
Elsevier

Published
DOI:10.1016/j.procir.2024.02.037

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

30 October 2026

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 122 (2024) 1077–1082

www.elsevier.com/locate/procedia

31st CIRP Conference on Life Cycle Engineering (LCE 2024)

A Study on the Cradle-to-Gate Environmental Impacts of Automotive Lithium-ion Batteries

Antonella Accardo[a,*], Giovanni Dotelli[b], Ezio Spessa[a]

[a]*Dipartimento Energia "Galileo Ferraris", CARS@Polito, Politecnico di Torino, c.so Duca degli Abruzzi 24, 10129 Torino, Italia*
[b]*Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

* Corresponding author. *E-mail address:* antonella.accardo@polito.it

Abstract

Several factors are influencing the spread of Electric Vehicles (EVs) in the automotive market. However, while battery-electric vehicles emit no tailpipe emissions, the manufacturing phase, particularly the manufacturing of the battery packs, can have significant environmental impacts. In addition, as the EV market expands, there will be a significant increase in demand for critical materials used in lithium-ion batteries, such as lithium, cobalt, and nickel. These materials are essential for producing high-performance batteries, and their global demand is expected to rise rapidly to meet the demands of the expanding market. This paper investigates the main challenges that need to be tackled to reach a sustainable path in the battery industry. A cradle-to-gate boundary is set to focus on raw material extraction, production of precursors, cell and module production, and battery pack assembly. In addition, because 7.8 million tons of EV batteries per year are expected to reach the end-of-life phase by 2040, a brief overview of the recycling issue is provided to investigate the potential usage of recycled material in the early stages of battery production.

© 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Keywords: LCA, Electric vehicles, Lithium-ion batteries; EV battery, Energy storage system

1. Introduction

The market for rechargeable batteries is expected to grow because of the increasing electrification market, rising environmental regulations, urbanization trends, and rising fuel costs [1–3]. Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs) use rechargeable battery packs to store energy [2,4,5]. The most commonly employed batteries are lithium-ion batteries [2,6,7], and among these, Nickel-Manganese-Cobalt oxide (NMC) cathode formulations have emerged as the dominant cathode chemistry [8], accounting for a 60% market share in 2022 [9]. Because Electric Vehicles (EVs) are characterized by zero tailpipe emissions, the key drivers in the development of lithium-ion batteries are environmental concerns [6]. In fact, EV batteries can have significant cradle-to-gate environmental impacts due to raw material extraction, material refining, and manufacturing [6,8,10–12].

According to published research, the carbon footprint of battery production ranges between 38–356 kg CO_{2eq}/kWh [13], while the cell manufacturing process consumes a significant amount of energy [14], which widely ranges between 83–700 kWh/kWh of battery cell capacity [6]. According to [15], the high variability and uncertainty in assessing the energy requirement is due to the fact that products vary in size and energy storage capacity, the plant size varies, and the battery manufacturing process and supply chain are currently unconstrained.

2212-8271 © 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 31st CIRP Conference on Life Cycle Engineering (LCE 2024)
10.1016/j.procir.2024.02.037

2. Methodology

This study aims to answer the research question of which are the main factors influencing the cradle-to-gate environmental impacts of EV batteries and the main challenges for a sustainable path in this sector. The boundary is cradle-to-gate, thus the life cycle phases related to extraction of raw materials, production of precursors, cell production, and battery pack assembly are investigated. Moreover, the recycling issue is included because of the potential usage of secondary materials as inputs to the manufacturing, i.e., for their potential inclusion in the cradle-to-gate boundary. The battery use phase is excluded from this investigation because it is strongly dependent on the assumed vehicle type, driving mission, battery pack configuration, and calculation approach (in fact, the environmental impacts of the use phase of the vehicle cannot be ascribed to the battery only). Lastly, the present paper mainly focuses on the NMC chemistry because it is currently the most used cathode.

3. Battery pack design

Typically, lithium-ion battery packs are designed and manufactured in a pack–module–cell structure [7,11,14,16] and include four main components: cells, mechanical structure, battery management system (BMS) and electronics, and cooling architecture. The overall battery pack design for any application depends greatly on the lithium-ion cells that are used, which determine the mechanical structure, the cooling architecture, the BMS and the overall packaging [2]. Battery pack system design also varies based on the vehicle architecture and desired system performance [2,7]. Moreover, because vehicles have different usage and power profiles, different battery pack designs are used to meet the different performance requirements, i.e., BEVs may have 20–24 kWh of onboard energy and even up to 100 kWh depending on the size of the vehicle [2].

3.1. Lithium-ion cell types

In the automotive industry, three types of battery cells are used: cylindrical, prismatic, and pouch cells [7]. The three types mainly differ in size, geometry, capacity, and supplied power [7], as reported in Table 1. The dimensions of the three cell types, particularly for the prismatic and pouch cells, vary between cell manufacturers and car manufacturers.

Cells can be installed into a standardized module, a mechanical structure that interconnects the cells into a single electromechanical unit, or directly into the pack structure [2]. Also, module sizes and shapes vary greatly between manufacturers and even within a single manufacturer due to the type of cells, the vehicle category, or the thermal management strategy (e.g., air, liquid) [2].

Table 1. NMC battery cell main parameters based on cell type.

Type	Capacity (Ah)	Assembly	Production volume	Production cost	Source
Cylindrical	2-3,5	Rolled	Billions/year	lowest	[2]
Pouch	15-40	Z-fold or stacked	low	high	[2,14]
Prismatic	4-250	Z-fold, stacked or rolled	low	high	[2]

4. Battery material extraction and pre-processing

4.1. Material breakdown of a typical lithium-ion cell

According to [14], the material composition of a lithium-ion battery pack determines its manufacturing process. For the material composition, battery cells consist of positive (cathode) and negative (anode) electrodes, current collectors, separator, electrolyte and additives [5,8,17]. The material that takes in and discharges the lithium ions is called active material. The NMC cells used in automotive applications are currently comprised of NMC cathodes and graphite anodes [5,8,17]. According to [18], PVDF-copolymers, which are dissolved in organic solvents such as N-methyl-pyrrolidone, are currently used as binders, whereas a new and greener alternative is to use as binders carboxy-methyl-cellulose and styrene-butadiene-rubber, which are dissolved and dispersed in water. The electrolyte is comprised of lithium fluorophosphate dissolved in organic solvents such as ethylene carbonate and dimethyl carbonate [14].

4.2. Raw material acquisition and critical raw materials

The European Commission has identified four critical raw materials for batteries production: cobalt, lithium, graphite, and nickel [20]. According to [9], the demand for these materials is increasing due to EV battery demand [9]. Furthermore, the sourcing of these materials is concentrated in few countries [20].

The rechargeable battery industry currently dominates the global cobalt market, accounting for 58% of cobalt use [1]. Rising cobalt prices and public concerns about cobalt mining have led to a shift towards chemistries with lower-cobalt ratios (e.g., NMC622, NMC811) [9]. After cobalt is sourced, refining is needed for most applications, including EV batteries [21]. The Democratic Republic of Congo (DRC) is the world's leading supplier of cobalt [1,21,22] while China is the main supplier of refined cobalt [1,21]. The growing cobalt demand is paired with high supply risk and low recycling rate [1,23]. Pure cobalt does not exist in nature and, because of its low concentration in ores, it is typically mined as a by-product of other commodities (i.e., copper, nickel and arsenic) [1,21,22,24]. In addition, 69% of cobalt used in manufactured products is not recycled and sent to landfill [1]. According to [20], the world mine production of cobalt is about 135 thousand tons in average over the period 2010-2014 while the global reserves (i.e., resources known to be economically feasible for extraction) account for 7 million tons.

Graphite holds 89% of the market share for anodes in commercial lithium-ion batteries [25]. Graphitic carbons can be divided into two groups: synthetic graphite and natural graphite. According to [24], both synthetic and natural graphite will be required to meet Europe's future needs.

Moreover, they have energy-intensive production routes (i.e., 230–260 MJ per kg graphite) [25]. Both are produced almost entirely in China, with additional surface modification occurring in Japan in some cases [24]. According to [20], the world mine production of natural graphite is about 1.1 million tons in average over the period 2010-2014 while the global reserves account for 230 million tons.

According to [9], lithium production has increased by 180% since 2017, but demand exceeded supply in 2022. Prices for lithium carbonate have also been steadily rising over the last two years [9]. Chile is the main supplier of lithium (i.e., 44%) [20,22]. According to [20], the world mine production of lithium is about 25 thousand tons in average over the period 2010-2014 while the global reserves account for 14 million tons.

Nickel is mainly produced in Cuba and Australia [22]. According to [20], the world mine production of nickel is about 2.2 million tons in average over the period 2010-2014 while the global reserves account for 80 million tons.

4.3. Material pre-processing

Regarding material pre-processing, the processes used to convert metal and compounds into the exact material compounds used in batteries involve mining, mineral processing, smelting, leaching, and refining [22]. Before battery cell manufacturing, the raw materials are extracted and then refined in chemicals (e.g., cobalt oxide, cobalt hydroxide, cobalt oxyhydroxide, cobalt carbonate, lithium carbonate, lithium hydroxide, and manganese oxide) [26]. The cathode can be made in different ways using different precursors. The NMC cathode is mainly produced through the following steps: precursor production, solid state synthesis, and post-treatment [17]. The precursor of the Cathode Active Material (pCAM) can be synthesized either via the carbonate or the hydroxide process route [17]. The latter is the most used route in industry [17]: cobalt, nickel, and manganese sulphates are used to produce through co-precipitation the hydroxide pCAM ($Ni_xCo_yMn_{1-x-y}(OH)_2$), then the Active Cathode Material (CAM) ($LiNi_xCo_yMn_{1-x-y}O_2$) is produced through solid state synthesis [17,27,28].

According to [19], the CAM powder is the most significant contributor to the cradle-to-gate energy consumption and environmental impact of NMC batteries.

5. Battery pack production

5.1. Manufacturing of the cells and modules

The information available in the literature on the energy use and greenhouse gas emissions of battery cell production is scarce, of varying quality and accuracy, and largely out of date [6]. China is currently the main producer of lithium-ion cells and EV battery packs, followed by Japan and South Korea [5]. In terms of current plant capacity, the Fraunhofer Society research factory in Germany has a theoretical output of 7 GWh/year electrode capacity, the SK Innovation plant in Georgia has a 9.8 GWh/year capacity, and the new CATL plant in Germany allows for 8 GWh/year capacity and plans to achieve 14 GWh/year capacity [6,29,30].

Lithium-ion cell manufacturing is described in [6,15,31–33]. The process can be broken down into three main stages: electrode production, cell assembly, and cell finishing [6].

First, additives, binders, and solvents are mixed with active materials through slurry mixing machines [6]. There is a distinction between mixing (dry mixing of active material, additives, and binder) and dispersing (wet mixing in which the solvent is added, dispersed, and homogenized) and the sequence of mixing and dispersing is electrode-specific [15,33].

Then, the slurry is transported to the coating step through pipelines or storage tanks and coated onto carrier foils made of copper for the anodes and aluminum for the cathodes [6,15,33,34]. A distinction must be made between batch, continuous, and discrete processes because the energy consumption significantly differ for each process type [15]. Then, the coated foils are cooled down to room temperature, compacted, and rolled up again [6,33]. Lastly, the coated foils are separated into thin strips, and dried once more [6].

At this point, if the cell has to be wounded, the dried rolls are wounded in a sequence anode-separator-cathode-separator around a winding mandrel (prismatic cell) or a center pin (cylindrical cell) [33]. Instead, if the cell has to be stacked (pouch cell), the dried rolls are unwound, separated through a punching tool in a continuous process, and then stacked [15,33]. Lastly, the current collector foils are contacted with the cell tabs, the cell is positioned in the cell housing and the electrolyte is filled in [15,33]. Because the cell assembly must be carried out under dry conditions, the coating and drying processes are the most energy-intensive production steps [6,18,33]. After the cells are assembled, they are charged and discharged in a climate-controlled camera, aged for 1-3 weeks, and tested [6,15,33].

For module assembly, the process is described in [35,36]. The cells can be connected in series and/or parallel. After testing, cells are scanned and sorted according to their performance. Then, a cell plasma cleaning machine is used for surface cleaning. In the case of prismatic cells, an electrically insulating joining medium (e.g., glue or adhesive tapes) is applied, and then the cells are stacked. Depending on the joining medium, solvent vapors are extracted. After completing the entire stacking, pressing, and bonding process, the core module is equipped with plastic insulation plates or foils used for heat dissipation and electrical insulation. The core module is tensioned by a clamping device, a bandage, or the module body itself. Contrarily to the prismatic cells, pouch and cylindrical cells are not glued. Because pouch cells expand and shrink in thickness during charging and discharging cycles, each cell is inserted into a frame, and the frames are held together by springs. In the case of cylindrical cells, the module itself prevents them from swelling. Then, cells are wired through an electrical connection, and the joints are tested for conductivity. The cells may be contacted through ultrasonic welding, laser welding or screw connections. The slave circuit board of the BMS is installed and joined by welding and/or screwing. The housing cover is mounted and fixed and the module is tested.

5.2. Assembly of the battery packs

A battery pack's mechanical structure, including single-pack or multiple packs [2], is crucial for structural stability, placement, underbody stiffness, crash protection, thermal management, and protection from the external environment [37]. For all these reasons, the design of each battery pack varies between applications and suppliers (e.g. 4S3P, 6S3P, 12S1P) [36]. The battery pack is usually made of aluminum, while a liquid or convective cooling system can be used for thermal management [38]. The assembly process of the battery pack is described in [36,39]. It involves preparing the housing, installing the cooling plate, modules, and electronic components, i.e., the BMS [33]. The process is completed with a final leak test.

5.3. Other factors influencing the environmental impacts

Energy consumption in lithium-ion manufacturing is influenced by plant scale, automation, and process optimization, resulting in divergent data in the literature [40]. According to [41], when small (i.e., [42]) and large-scale (i.e., [41]) plants are compared, the electricity demand per kWh cell storage capacity is reduced by 58% in large scale plant. Moreover, according to [40], not only energy consumption, but also material consumption is influenced by economies of scale. Another factor influencing the energy consumption of lithium-ion battery manufacturing is the calculation approach [40,43]. Two different approaches have been used so far, namely top-down and bottom-up, which have been demonstrated to generate significantly different results. Top-down calculates specific energy consumption based on total plant energy consumption and economic or mass allocation, while bottom-up uses data traceability systems at and acquires energy consumption each manufacturing sub-process. Lastly, the country's electricity mix significantly impacts the carbon footprint results [6] due to the diverse sources in each location (e.g., natural gas, solar, wind, nuclear, coal, oil, etc.).

6. Circularity

7.8 million tons of EV batteries per year are expected to reach the End-of-Life (EoL) by 2040 [44], while the recycling market is expected to reach 18 billion dollars in 2030 [45], highlighting the need for harmonizing battery logistics for circularity [24,45]. Efficient collection, handling, sorting, and dismantling of EoL batteries are crucial steps in reintroducing batteries into the battery value chain [24]. Dependency on virgin critical raw materials can be decreased by extending product life as well as by properly recycling the EoL materials [45]. Moreover, according to [45], cooperation between manufacturer, user, and recycler is a key to implement circularity. Currently, a knowledge gap exists concerning the environmental impacts of diverse recycling routes and the potential usage of secondary materials during manufacturing as their environmental impact may outweigh their benefits [40,44,46].

6.1. Recycling

Currently, South Korea is at the forefront of lithium-ion battery recycling, but other companies are emerging, and some OEMs are putting in place their own recycling [45]. Today's recycling processes have been designed to recover rich metals, paying less attention to the other battery materials [45,47]. However, the recycling processes need to improve to recover a major fraction of materials to be compliant with the EU's new regulation on waste batteries [48].

Among the lithium-ion battery components, cathodes can be recycled while anode recycling is under investigation [45]. On the cathode side, cobalt can be recycled and reused numerous times. According to [24], recovering cobalt and cobalt compounds from EoL materials with high recycling rates is economically feasible, while, according to [21], it is not only feasible, but cobalt recovery is one of the primary drivers that makes recycling of lithium-ion batteries appealing to recyclers. According to [49], in fact, battery recycling is the main source of secondary cobalt, accounting for 65% of the total sources. According to [40], the shift towards nickel-rich cathodes and the consequent reduction of cobalt content may become an economic disincentive for battery recycling.

Before they enter the recycling route, EoL batteries must be discharged for safety reasons [24]. According to [24], it is necessary to develop new discharge technologies that do not waste batteries' residual energy but recover it. Recycling processes can be categorized as pyrometallurgical, hydrometallurgical, or direct recycling [22,40,45]. In the pyrometallurgical route, the battery is fed into a smelting furnace. The high temperature of the process allows for the recovery of an alloy of nickel, copper, and cobalt, while lithium and manganese exit as slag [45]. The hydrometallurgical route requires a pre-treatment that generates the so-called black mass [45]. Then, the black mass can be dissolved in sulfuric acid, and the metals can be separated in several steps of solvent extraction and recovered as sulphates [45]. The energy consumption during the hydrometallurgical route is lower than that of the pyrometallurgical route, but wastewater treatment is needed [45]. Moreover, contrary to the pyrometallurgical route, the hydrometallurgical route allows for the recovery of lithium, manganese, and aluminum [12]. Both in the pyrometallurgical and hydrometallurgical routes, recovered metal alloys and complex intermediates require reprocessing and purification into chemical precursors [24]. Direct recycling, instead, aims to reuse the cathode, avoiding material dissolution and repurification [45,50]. Lastly, the environmental impacts related to recycling lithium-ion batteries do not depend only on the recycling route but also on the cell chemistry [40].

6.2. Usage of secondary materials

As a regulatory requirement, mandatory levels of recycled content will be put in place in the European Union with the new regulation on waste batteries [48]. According to [51], in the lead-acid battery market, secondary lead is already used in new batteries. Although in 2021, Northvolt produced its first NMC cell made with 100% recycled nickel, manganese, and

cobalt [52], the major limiting factor in the usage of secondary materials in new batteries are the availability of raw materials, which will be available after 10-15 years, and their impact on battery performance [51]. Moreover, while battery grade materials are primarily produced using well-developed processes designed for virgin raw materials [24], novel recycling technologies have to be researched or optimized to obtain high-quality recycled materials. Regarding reduction of contaminants, [53] investigates the effect of aluminum impurities in secondary materials for NMC cathodes, while [54] presents a novel purification method for reducing aluminum and copper contaminants in black mass. For the estimation of the batteries produced from secondary materials, [55] compares the performances of NMC cathodes produced from virgin and secondary materials, while [56] compares three scenarios to assess the performance of lithium-ion cathodes produced from recycled materials. Also, in [57], a process for recycling NMC batteries is presented, exhibiting similar electrochemical behavior with the virgin precursor, while in [58], guidelines are provided on how to design secondary lithium-ion batteries to avoid performance losses. Lastly, in [59], nickel oxide is recovered from EoL lithium-ion batteries, exhibiting performance suitable to be reused in other batteries.

7. Conclusions

This paper investigates the crucial factors influencing the cradle-to-gate environmental impacts of EV batteries, focusing on battery pack design, raw material extraction, precursor production, battery pack production, and circularity.

The most critical phases of the life cycle of lithium-ion batteries are managed in a few countries. The DRC and Chile are the main providers of cobalt and lithium, respectively. China is the main provider of synthetic and natural graphite, refined cobalt, as well as lithium-ion cells and batteries. South Korea is leading in battery recycling, but some OEMs are putting in place their own recycling.

On the raw material extraction side, the European Commission designated cobalt, lithium, graphite, and nickel as critical raw materials for battery production, urging for a sustainable supply chain, improved cell performance and durability, and recycling technology innovation.

On the manufacturing side, the battery pack design varies based on the cell type and intended application, i.e., vehicle type and usage profile. The information available on the energy use and carbon footprint of battery production is spread, scarce, uncertain, and often out of date. Energy and material consumption during manufacturing highly depend on plant size, automation, process optimization, plant location, and calculation approach. Moreover, the material composition of the battery pack determines which processes are involved in manufacturing, and the energy expenditure and environmental impacts. Batch, continuous, and discrete electrode coating processes result in diverse energy consumptions. Lastly, electrode coating and drying are the most energy-intensive steps.

On the circularity side, there is an increasing importance of putting in place an efficient circular strategy. This involves efficient collection, handling, sorting, dismantling of EoL batteries, and innovative recycling techniques. Moreover, according to the new regulation on waste batteries, the European Commission is going to put in place mandatory minimum recycled contents and recycling efficiencies in the EU. Nonetheless, the usage of secondary materials still has no evidence in the market, mainly because of the availability of secondary materials and their impact on battery performance.

Acknowledgment

This work was supported by the Center for Automotive Research and Sustainable Mobility (CARS@Polito).

References

[1] Dehaine Q, Tijsseling LT, Glass HJ, Törmänen T, Butcher AR. Geometallurgy of cobalt ores: A review. Miner Eng 2021;160:106656. https://doi.org/10.1016/j.mineng.2020.106656.

[2] Warner J. 7 - Lithium-Ion Battery Packs for EVs. In: Pistoia G, editor. Lithium-Ion Batter., Amsterdam: Elsevier; 2014, p. 127–50. https://doi.org/10.1016/B978-0-444-59513-3.00007-8.

[3] Ding Y, Cano ZP, Yu A, Lu J, Chen Z. Automotive Li-Ion Batteries: Current Status and Future Perspectives. Electrochem Energy Rev 2019;2:1–28. https://doi.org/10.1007/s41918-018-0022-z.

[4] Gallagher KG, Nelson PA. Manufacturing Costs of Batteries for Electric Vehicles. Lithium-Ion Batter., Elsevier; 2014, p. 97–126. https://doi.org/10.1016/B978-0-444-59513-3.00006-6.

[5] Tolomeo R, De Feo G, Adami R, Sesti Osséo L. Application of Life Cycle Assessment to Lithium Ion Batteries in the Automotive Sector. Sustainability 2020;12:4628. https://doi.org/10.3390/su12114628.

[6] Degen F, Schütte M. Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production. J Clean Prod 2022;330:129798. https://doi.org/10.1016/j.jclepro.2021.129798.

[7] Zwicker MFR, Moghadam M, Zhang W, Nielsen CV. Automotive battery pack manufacturing – a review of battery to tab joining. J Adv Join Process 2020;1:100017. https://doi.org/10.1016/j.jajp.2020.100017.

[8] Kallitsis E, Korre A, Kelsall G, Kupfersberger M, Nie Z. Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. J Clean Prod 2020;254:120067. https://doi.org/10.1016/j.jclepro.2020.120067.

[9] International Energy Agency. Global EV Outlook 2023: Catching up with Climate Ambitions. OECD; 2023. https://doi.org/10.1787/cbe724e8-en.

[10] Cusenza MA, Bobba S, Ardente F, Cellura M, Di Persio F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. J Clean Prod 2019;215:634–49. https://doi.org/10.1016/j.jclepro.2019.01.056.

[11] Vittorio ND, Accardo A, Spessa E, Viscido L, Tam E. LCA and LCC of a Li-ion Battery Pack for Automotive Application. Warrendale, PA: SAE International; 2023. https://doi.org/10.4271/2023-24-0170.

[12] Accardo A, Dotelli G, Musa ML, Spessa E. Life Cycle Assessment of an NMC Battery for Application to Electric Light-Duty Commercial Vehicles and Comparison with a Sodium-Nickel-Chloride Battery. Appl Sci 2021;11:1160. https://doi.org/10.3390/app11031160.

[13] Ellingsen LA-W, Hung CR, Strømman AH. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. Transp Res Part Transp Environ 2017;55:82–90. https://doi.org/10.1016/j.trd.2017.06.028.

[14] Yuan C, Deng Y, Li T, Yang F. Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CIRP Ann 2017;66:53–6. https://doi.org/10.1016/j.cirp.2017.04.109.

[15] Thomitzek M, von Drachenfels N, Cerdas F, Herrmann C, Thiede S. Simulation-based assessment of the energy demand in battery cell manufacturing. Procedia CIRP 2019;80:126–31. https://doi.org/10.1016/j.procir.2019.01.097.

[16] Lelli E, Musa A, Batista E, Misul DA, Belingardi G. On-Road Experimental Campaign for Machine Learning Based State of Health Estimation of High-Voltage Batteries in Electric Vehicles. Energies

2023;16. https://doi.org/10.3390/en16124639.
[17] PEM, VDMA. Manufacturing of lithium-ion battery cell components, n.d.
[18] Pettinger K-H, Dong W. When Does the Operation of a Battery Become Environmentally Positive? J Electrochem Soc 2016;164:A6274. https://doi.org/10.1149/2.0401701jes.
[19] Dai Q, Kelly JC, Gaines L, Wang M. Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. Batteries 2019;5:48. https://doi.org/10.3390/batteries5020048.
[20] European Commission. Report on Raw Materials for Battery Applications. 2018.
[21] Cobalt Institute. Cobalt factsheet 2023. https://www.cobaltinstitute.org/wp-content/uploads/2023/08/Cobalt_Factsheet.pdf (accessed October 11, 2023).
[22] Arshad F, Lin J, Manurkar N, Fan E, Ahmad A, Tariq M-N, et al. Life Cycle Assessment of Lithium-ion Batteries: A Critical Review. Resour Conserv Recycl 2022;180:106164. https://doi.org/10.1016/j.resconrec.2022.106164.
[23] European Commission. European Critical Raw Materials Act. Eur Comm - Eur Comm 2023. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661 (accessed October 9, 2023).
[24] Trapp V, Zygmunt M, Hilario F, Ramon NG, Míguez JM, Philippot M, et al. Batteries Europe ETIP WG2: Raw Materials and Recycling Roadmap 2021.
[25] Engels P, Cerdas F, Dettmer T, Frey C, Hentschel J, Herrmann C, et al. Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. J Clean Prod 2022;336:130474. https://doi.org/10.1016/j.jclepro.2022.130474.
[26] Hosokawa Micron Corporation. LIB Cathode, Precursors of Cobalt Based Manganese 2023. https://www.hosokawamicron.co.jp/en/product/industries/detail/250.html (accessed October 20, 2023).
[27] Dai Q, Spangenberger J, Ahmed S, Gaines L, Kelly JC, Wang M. EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model. 2019. https://doi.org/10.2172/1530874.
[28] Emilsson E, Dahllöf L. Lithium-Ion Vehicle Battery Production 2019.
[29] CATL. CATL's German plant kicks off cell production 2022. https://www.catl.com/en/news/1046.html (accessed October 9, 2023).
[30] SK Innovation. History < Introduction < Company | SKI 2019. https://www.skinnovation.com/company/history (accessed October 9, 2023).
[31] Degen F, Krätzig O. Modeling Large-Scale Manufacturing of Lithium-Ion Battery Cells: Impact of New Technologies on Production Economics. IEEE Trans Eng Manag 2023:1–17. https://doi.org/10.1109/TEM.2023.3264294.
[32] Degen F, Krätzig O. Future in Battery Production: An Extensive Benchmarking of Novel Production Technologies as Guidance for Decision Making in Engineering. IEEE Trans Eng Manag 2022:1–19. https://doi.org/10.1109/TEM.2022.3144882.
[33] PEM, VDMA. Lithium-ion battery cell production process., 2018.
[34] Agarwal A, Gilden D, Kiridena R, Wiers K. Design and Fabrication of a Li-Ion Battery Electrode Coating Fixture 2015.
[35] Shandong Huiyao Laser Technology Co., Ltd. Semi Automatic Lithium Battery Pack Production Line. Shandong Huiyao Laser Technol Co Ltd 2023. https://www.hyenergymachine.com/products/semi-automatic-lithium-battery-pack-production-line.html (accessed October 12, 2023).
[36] PEM, VDMA. Battery Module and Pack Assembly process, 2018.
[37] Belingardi G, Scattina A. Battery Pack and Underbody: Integration in the Structure Design for Battery Electric Vehicles—Challenges and Solutions. Vehicles 2023;5:498–514. https://doi.org/10.3390/vehicles5020028.
[38] Bernagozzi M, Miché N, Georgoulas A, Rouaud C, Marengo M. Performance of an environmentally friendly alternative fluid in a loop heat pipe-based battery thermal management system. Energies 2021;14. https://doi.org/10.3390/en14227738.
[39] Puglia S. Process performance and envoironmental impact assessment in e-mobility industrial launch. laurea. Politecnico di Torino, 2023.
[40] Erakca M, Pinto Bautista S, Moghaddas S, Baumann M, Bauer W, Leuthner L, et al. Closing gaps in LCA of lithium-ion batteries: LCA of lab-scale cell production with new primary data. J Clean Prod 2023;384:135510. https://doi.org/10.1016/j.jclepro.2022.135510.
[41] Chordia M, Nordelöf A, Ellingsen LA-W. Environmental life cycle implications of upscaling lithium-ion battery production. Int J Life Cycle Assess 2021;26:2024–39. https://doi.org/10.1007/s11367-021-01976-0.
[42] Ellingsen LA-W, Majeau-Bettez G, Singh B, Srivastava AK, Valøen LO, Strømman AH. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. J Ind Ecol 2014;18:113–24. https://doi.org/10.1111/jiec.12072.
[43] Peters JF, Baumann M, Zimmermann B, Braun J, Weil M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renew Sustain Energy Rev 2017;67:491–506. https://doi.org/10.1016/j.rser.2016.08.039.
[44] Wang Y, Tang B, Shen M, Wu Y, Qu S, Hu Y, et al. Environmental impact assessment of second life and recycling for LiFePO4 power batteries in China. J Environ Manage 2022;314:115083. https://doi.org/10.1016/j.jenvman.2022.115083.
[45] Hool A, Schrijvers D, van Nielen S, Clifton A, Ganzeboom S, Hagelueken C, et al. How companies improve critical raw material circularity: 5 use cases. Miner Econ 2022;35:325–35. https://doi.org/10.1007/s13563-022-00315-5.
[46] Bontempi E. How to perform a material recovery sustainability evaluation preliminary to LCA? Resour Environ Sustain 2022;9:100074. https://doi.org/10.1016/j.resenv.2022.100074.
[47] Islam MT, Iyer-Raniga U. Lithium-Ion Battery Recycling in the Circular Economy: A Review. Recycling 2022;7:33. https://doi.org/10.3390/recycling7030033.
[48] European Commission. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. 2020.
[49] Cobalt Value Chain Mapping: Navigating the Journey 2021. https://www.cobaltinstitute.org/cobalt-sourcing-responsability/cobalt-value-chain/ (accessed October 20, 2023).
[50] Montoya AT, Yang Z, Dahl EU, Pupek KZ, Polzin B, Dunlop A, et al. Direct Recycling of Lithium-Ion Battery Cathodes: A Multi-Stage Annealing Process to Recover the Pristine Structure and Performance. ACS Sustain Chem Eng 2022;10:13319–24. https://doi.org/10.1021/acssuschemeng.2c02643.
[51] Position paper on Recycled Content in the new Batteries Regulation. EUROBAT n.d. https://www.eurobat.org/resource/position-paper-on-recycled-content-in-the-new-batteries-regulation/ (accessed October 12, 2023).
[52] Transport & Environment. Lithium recycling factsheet. 2022.
[53] Krüger S, Hanisch C, Kwade A, Winter M, Nowak S. Effect of impurities caused by a recycling process on the electrochemical performance of Li[Ni0.33Co0.33Mn0.33]O2. J Electroanal Chem 2014;726:91–6. https://doi.org/10.1016/j.jelechem.2014.05.017.
[54] Fink K, Gasper P, Major J, Brow R, Schulze MC, Colclasure AM, et al. Optimized purification methods for metallic contaminant removal from directly recycled Li-ion battery cathodes. Front Chem 2023;11.
[55] El Mounafia N, Aannir M, Hakkou R, Zaabout A, Saadoune I. Comparative performance analysis of NMC cathodes elaborated from recovered and commercial raw materials: A low-temperature molten salt approach for extracting critical metals from end-of-life lithium-ion batteries. Mater Today Commun 2023;36:106603. https://doi.org/10.1016/j.mtcomm.2023.106603.
[56] Al-Shammari H, Farhad S. Performance of Cathodes Fabricated from Mixture of Active Materials Obtained from Recycled Lithium-Ion Batteries. Energies 2022;15. https://doi.org/10.3390/en15020410.
[57] Ilyas S, Srivastava RR, Kim H. Cradle-to-cradle recycling of spent NMC batteries with emphasis on novel Co2+/Ni2+ separation from HCl leached solution and synthesis of new ternary precursor. Process Saf Environ Prot 2023;170:584–95. https://doi.org/10.1016/j.psep.2022.12.045.
[58] Lagnoni M, Latini D, Nicolella C, Tognotti L, Bertei A. Design guidelines for secondary lithium-ion battery electrodes to overcome performance limitations of recycled cathode materials. J Energy Storage 2022;50:104237. https://doi.org/10.1016/j.est.2022.104237.
[59] Pham HD, Krishnan SG, Wang T, Fernando JFS, Padwal C, Golberg DV, et al. Upcycling of nickel oxide from spent Ni-MH batteries as ultra-high capacity and stable Li-based energy storage devices. Sustain Mater Technol 2023;36:e00602. https://doi.org/10.1016/j.susmat.2023.e00602.