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Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles

Xin Sun[a,b,c], Xiaoli Luo[a,b], Zhan Zhang[a,b], Fanran Meng[d], Jianxin Yang[a,b] *

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, No.18 Shuangqing road, Haidian District, Beijing 100085, China

[b]College of Resources and Environment, University of Chinese Academy of Sciences, No. 80 East Zhongguancun Road, Haidian District, Beijing, 100190, China

[c]China Automotive Technology and Research Center Co., Ltd, No. 68 East Xianfeng Road, Dongli District, Tianjin 300300, China

[d] Sustainable Process Technologies Group, Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, UK

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Abstract

This study evaluated and quantified the life cycle environmental impacts of lithium-ion power batteries (LIBs) for passenger electric vehicles to identify key stages that contribute to the overall environmental burden and to find ways to reduce this burden effectively. Primary data for the assessment were collected onsite from the one Chinese leading LIB supplier, two leading cathode material producers and two battery recycling corporations from 2017 to 2019. Six environmental impact categories, including primary energy demand (PED), global warming potential (GWP), acidification potential (AP), photochemical oxidant creation potential (POCP), eutrophication potential (EP) and human toxicity potential (HTP), were considered in accordance with the ISO 14040/14044 standards. The results indicate that material preparation stage is the largest contributor to the LIB's life cycle PED, GWP, AP, POCP, EP and HTP, with the cathode active material, wrought aluminum and electrolytes as the predominant contributors. In the production stage, vacuum drying and coating and drying are the two main processes for all the six impact categories. In the end-of-life stage, waste LIBs recycling could largely reduce the life cycle POCP and HTP. Sensitivity analysis results replacing NCM 622 by NCM 811 as the cathode active material could increase all the six environmental impacts. We hope this study is helpful to reduce the uncertainties associated with the life cycle assessment of LIBs in existing literatures and to identify opportunities to improve the environmental performance of LIBs within the whole life cycle.

Keywords Lithium-ion power battery; Battery electric vehicle; Life cycle assessment; Battery recycling

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1 Introduction

To save energy and reduce environmental emissions from the automotive industry, the Chinese government has launched numerous policies and programs to promote new energy vehicles (NEVs), which include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCVs). In 2009, China launched the "Ten Cities and Thousand Vehicles" project to promote NEVs. From 2009 to 2012, a total of 17,000 NEVs were promoted (MOST et al., 2009). Since 2014, China has been in the stage of large-scale promotion and application of NEVs. In 2018, the cumulative sales of NEVs reached 3.0 million, accounting for more than 53% of global cumulative sales (Wan, 2019). China has become the world's largest market for NEVs. By the end of 2019, the stock of NEVs reached 3.8 million, accounting for 1.5% of the total vehicles in China (Jiang, 2020).

As the core component of NEVs, the capacity of power batteries has also increased by a significant amount each year. China has been the world's largest power battery producer (MIIT, 2017). The cumulative installed capacity of power batteries in China reached 144 GWh by the end of 2018, which represents the largest power battery market worldwide (MIIT, 2019).

Currently, lithium-ion power batteries (LIBs), such as lithium manganese oxide ($LiMn_2O_4$, LMO) battery, lithium iron phosphate ($LiFePO_4$, LFP) battery and lithium nickel cobalt manganese oxide ($LiNi_xCo_yMn_zO_2$, NCM) battery, are widely used in BEVs in China. According to the data from China Automotive Technology and Research Center Co., Ltd, NCM batteries accounted for 42% of the cumulative installed capacity of power batteries and 77% of the cumulative installed capacity of passenger BEVs until 2018 in China. Current types of NCM batteries in Chinese market include old-fashioned NCM 111 ($LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$), state-of-art NCM 622 ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) and upcoming technology NCM 811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) while NCM 622 batteries have been the most commonly used in electric passenger vehicles in China (CATARC and BIT, 2019).

NEV sales will maintain long-term growth in China benefiting from various policy supports. The "Technology Roadmap For Energy Saving And New Energy Vehicles"(TRESNEV Steering Commitee China-SAE, 2016) shows that the total sales of NEVs is forecasted to exceed 5 million in 2025 and 15 million in 2030. This projection will lead to a huge number of demand and disposal of power batteries in China in the near future.

With the fast expansion of NEVs, China will be facing with challenges of waste power battery recycling and disposal. The capacity of decommissioned power batteries was 1.2 GWh in 2018 in China, and it is expected to be more than 200,000 tons by 2020, which indicates that about 25 GWh of power batteries need to be recycled and reused by 2020 (MIIT, 2019).

The environmental impacts associated with LIBs within the life cycle are key challenges that restrict the sustainable development of NEVs. First, LIBs contain various types of valuable metal materials, which can produce large amount of pollutants in the exploitation and extraction stages. In addition, the assembly process of LIBs can be energy intensive (Dai et al., 2019; Ellingsen et al., 2017). Finally, the improper recycling and waste disposal processes may incur negative environmental pollutions and human toxicity. Therefore, an environmental assessment is required to quantify the overall environmental impacts of LIBs in BEVs application from a full life cycle perspective.

To address the gaps in environmental aspects of LIBs production and promote NEVs development in China. In this study, we aim to quantify the life cycle environmental impacts of NCM 622 batteries for electric passenger vehicles using the primary data collected from the latest and representative onsite investigations in China covering material production, LIB production and battery recycling plants. Inventory data is also supplemented by Ecoinvent 3.0, GREET 2018 database (ANL GREET, 2018) where available. The results can help identify the key contributors to the LIB life cycle environmental impacts and propose strategies to reduce these impacts effectively.

2 Literature review

Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from material preparation, via production and use phases, to waste management (ISO, 2006). Until now, there have been several LCA studies of LIBs. Notter et al. (2010) conducted an early LCA study of LMO batteries and the contributions to the environmental burden caused by different battery materials were analyzed. USEPA (2013) conducted a LCA study to bring together and use life cycle inventory data directly provided by LIB suppliers, manufacturers, and recyclers. (Ellingsen et al., 2014) studied the cradle-to-gate environmental impacts of NCM batteries by using midpoint indicators, which include 13 impact categories. Kim et al. (2016) chose a commercial BEV and assessed the life cycle greenhouse gas (GHG) emissions and other air emissions of traction batteries.

In addition, other scientists have provided richer perspectives and deeper discussions. MajeauBettez et al. (2011) compared the environmental impacts of three different LIBs, NCM, NiMH, and LFP batteries, during production and operation phases. They concluded that NiMH batteries have the highest environmental burden, followed by NCM and then LFP. Li et al. (2014) and Deng et al. (2017) reported the environmental impacts of next-generation LIBs compared with conventional LIBs to support the selection and development of future LIBs. Ellingsen et al. (2017) pointed out that both Notter et al. (2010) and Dunn et al. (2012) neglected processes in cell manufacturing and therefore underestimated the energy demand. Ellingsen et al. (2017) indicated that USEPA (2013) reported very different energy use associated with cell manufacturing and pack assembly for NCM, LFP, and LMO batteries without clear explanations. Peters et al. (2017) provided a review of LCA studies on LIB and found that only a few publications contributed original life cycle inventory (LCI) data. Peters et al. (2017) pointed that the majority of existing studies focus on GHG emissions or energy demand only, while the impacts in other categories such as toxicity might be even more important. Dai et al. (2019) analyzed the cradle-to-gate energy use, GHG emissions, SO_x, NO_x, PM_{10} emissions, and water consumption associated with current industrial production of NCM batteries. Dai et al. (2019) pointed out that the existing LCA studies of LIB, including the studies conducted by Notter et al. (2010), MajeauBettez et al. (2011), Dunn et al. (2012) and (Ellingsen et al., 2014) were carried out when automotive LIBs were at their early commercialization stage which might be different from current practices. Besides, Dai et al. (2019) also identified knowledge gaps, such as the LCI data for graphite, $LiPF_6$, and the separator, which should be improved in future studies.

Moreover, some studies have deeply discussed the environmental impacts during the recycling process of LIBs. (Dunn et al., 2012) calculated the energy consumed and the air emissions generated when recycling LMO batteries in the U.S. and estimated that direct recycling could avoid 48% energy consumption associated with primary material production. (Hendrickson et al., 2015) distinguished hydrometallurgical and pyrometallurgical recycling methods of LMO, LFP, and NCM batteries, and the results showed that hydrometallurgy achieves greater energy savings.

Although several LCA studies assessed LIBs, they presented significantly different results with large uncertainties associated with data and results (Dai et al., 2019; Ellingsen et al., 2017; Peters et al., 2017). First, for the background data, most of these studies used secondary LCI databases, disunified LCI databases, or literature publications as data sources. In addition, for the foreground data, most studies were conducted based on previous literature publications, engineering calculations and secondary data, and therefore did not reflect the current commercial-scale automotive LIB production. Furthermore, for the life cycle stages, most studies only focused on production (cradle-to-gate), while only a few have clearly assessed the end-of-life stage. Therefore, it is essential to assess the life cycle environmental impacts of LIBs with primary life cycle data in the context of China and identify the potential for reducing the environmental impacts of LIBs.

3 Methods

3.1 Goal and scope

The goal of this study is to assess the environmental impacts of NCM batteries within the battery life cycle and to identify the key contributory processes exploring improvement opportunities. In this study, the functional unit is defined as 1 kWh of the NCM 622 pack for a passenger BEV. As shown in Figure 1, the system boundaries cover the life cycle stages of the LIB, including material preparation, production and end-of-life stages. The use stage is excluded in the LIB's system boundaries due to the large uncertainty of some key parameters, such as the real world driving cycles, different charging behaviors, battery replacement times, and the lack of unified allocation method of the electricity consumption of the battery pack.

This study was conducted in accordance with the principles of the ISO 14040 series standards for LCA.(ISO, 2006) SimaPro 8 software (PRé Sustainability, Netherlands) was used as a support tool to establish the LCA model and perform the impact assessment.

3.2 Methods and databases

To collect the cradle to grave primary LCI data, this study conducted onsite investigations in six leading LIB factories (with a total China market share of over 75% in 2018), five leading LIB material producer and two battery recycling corporations from 2017 to 2019 in China. Considering the representative and completeness of the onsite data, this study chose the primary data from two Chinese leading LIB suppliers (world's top three), two leading cathode material producer (world's top five), and two battery recycling corporation (one owned by the world's top three LIB supplier, and the other one is the world's leading waste battery and cobalt nickel tungsten rare metal recycling corporation). A sensitivity analysis has been conducted to evaluate the data uncertainties.

The upstream materials and energy flows for NCM 622 precursor and NCM 622 production were obtained from onsite investigations of two leading cathode material producer in 2018 in China, which are of the world's top five NCM suppliers（Tables S 2 and S 3). For the LCI data of dimethyl carbonate (DMC), polyvinylidene fluoride

(PVDF) and electronic parts, the foreground data were acquired from the GREET 2018 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model,(ANL GREET, 2018). The background data were primarily based on the China Automotive Life Cycle Database (CALCD) (Sun et al., 2015; Sun et al., 2017) with Ecoinvent 3.0 database as supplements. The CALCD, a local Chinese LCI database developed by the China Automotive Technology and Research Center, is a process-based life cycle database. Detailed data source information is listed in Table S 1, Table S 2 and Table S 3 in the Supporting Information.

The CML-IA baseline V3.02 method developed by the Institute of Environmental Sciences of Leiden University is selected as the base method. Six impact categories, including primary energy demand (PED), global warming potential (GWP), acidification potential (AP), photochemical oxidant creation potential (POCP), eutrophication potential (EP) and human toxicity potential (HTP) are chosen from this approach to assess the impact characterization results, and these categories are easily communicated, of general interest, and important with respect to LIBs. As a comparison, ReCiPe Midpoint (H) V1.11 / World Recipe H method is applied to present ten impact categories. The normalization and weighting phases are not included in this study.

3.3 Life cycle inventory analysis

3.3.1 Material preparation

For the investigated NCM 622 pack in this study, which is used by one passenger car, the pack energy capacity is 72.5 kWh, the pack weight is 630 kg, and the cycle life is 2000 times or 10 years. The energy density of the battery is 180 Wh/kg at the cell level and 115 Wh/kg at the pack level. Figure 2 shows the material compositions of a 1 kWh LIB pack, including the cell materials and battery components. The cathode active material, NCM 622, accounts for 26.7% of the total LIB mass. The anode active material, graphite, accounts for 15.3% of the total LIB mass. The wrought aluminum used for the cathode electrode and enclosure represents 23.0% of the total LIB mass. The copper used for the anode electrode and terminal represents 8.6% of the total LIB mass. The electrolytes, including $LiPF_6$, Ethylene Carbonate (EC) and DMC, account for 18.5% of the total LIB mass. The polypropylene used for the separator comprises 1.5% of the total LIB mass. The battery components, including steel, thermal insulation, coolant electronic parts and wrought aluminum, account for 9.3% of the LIB mass. Detailed material compositions of NCM 622 pack are presented in Table S 4 in the Supporting Information.

3.3.2 Production stage

The production stage of NCM 622 battery includes cell manufacturing, module and pack assembly. Cell manufacturing consists of the mixing, coating and drying, vacuum drying and formation processes. The primary data are based on a cell production capacity of nearly 30 GWh/yr. A process-based and attributional approach was used to compile the inventory data.

In order to manufacture 1 kWh of cell, 72.0 MJ of electricity and 34.0 MJ of steam are consumed. The coating and drying process (dry room) consumes 25.2 MJ (35%) of electricity and 17.0 MJ (50%) of steam for dehumidification. Subsequently, the electrode vacuum drying process consumes 28.8 MJ (40%) of electricity and 17.0 MJ (50%) of steam. Then, the formation process consumes 10.8 MJ (15%) of electricity. In addition, the mixing process and module and pack assembly process consumes 3.6 MJ (5%) of electricity, respectively. Energy consumption for per kWh NCM 622 battery production are presented in Table S6 in the Supporting Information.

Therefore, considering the 4 MJ/kWh electricity required to fully charge the battery, it is estimated that the total energy consumption of the LIB production is 110.0 MJ/kWh. The vacuum drying contributes the largest share (42%) of the total energy demand, followed by the coating and drying process (38%). Formation accounts for 10% of the total energy demand. While the contribution of mixing process and module and pack assembly process are relatively lower than the other processes, accounting for 3%, respectively. Besides, 33.9 kg water is used in the mixing process, and 20 g particulate matter is emitted during the 1 kWh cell manufacturing.

3.3.3 End-of-life stage

The current main recycling technology for waste LIB include physical dismantling (Saeki et al., 2004; Zhang et al., 2007), pyrometallurgy (Bahat et al., 2007; Song et al., 2013) and hydrometallurgy (Chen et al., 2015; Nayaka et al., 2016; Sun and Qiu, 2012). In hydrometallurgy the materials in LIBs are selectively dissolved by chemical solvents and the metal elements are separated in the leachate. It could be used alone or in combination with pyrometallurgy and does not require high equipment and processing cost (Nayaka et al., 2016). Under optimized experimental conditions the recovery efficiency of 98.7% for Ni, 97.1% for Mn, 98.2% for Co and 81.0% for Li could be attained (Chen et al., 2015). Due to the wide application of hydrometallurgical methods for recycling waste LIBs in China and in order to simplify our model, it is assumed that used NCM 622 batteries are 100% collected and recycled by hydrometallurgical methods to feed into NCM 622 production loop and thus avoid the production of primary materials, such as steel, aluminum, polypropylene and copper. From the onsite investigations in two Chinese large waste battery recycling corporations, including the one owned by the world's top three LIB supplier (Xie et al., 2015), and the other one that is the world's leading waste battery and cobalt nickel tungsten rare metal recycling corporation, the inventory data associated with the recycling of 1 kWh of waste LIBs are shown in Table 1. The primary data is based on a waste battery treatment capacity of 3,000t/yr.

Table 1 Inventory Data for the Recycling of 1 kWh Waste NCM 622 Lithium-Ion Power Battery

Category	Name	Value	Unit
Materials	Waste NCM battery	1.0	kwh
	H_2SO_4 (98%)	9.6	kg
	HCl (30%)	0.3	kg
	NaOH (30%)	16.3	kg
	Na_2CO_3	0.2	kg
	Ammonia (28%)	1.0	kg
	Extracting reagent P507	17.4	g
	Kerosene	42.5	g
	H_2O_2	3.2	kg
	Industrial water	121.6	kg
	Li_2CO_3	1.1	kg
Energy	Electricity	20.3	kWh
	Natural gas	1.2	m3
Emissions	Wastewater	86.9	kg
	Ammonia nitrogen	0.5	g
	CO_2	0.6	kg
	SO_2	0.01	kg
	Dust	3.1	kg
Recycled Substances	Polypropylene	0.1	kg
	Copper	0.7	kg
	Aluminum	1.8	kg
	Steel	0.1	kg
	NCM Precursor	2.1	kg

4 Results and Discussion

4.1 Life cycle assessment results

The LCA results for the six environmental impact categories are shown in Figure 3. The material preparation stage is the primary contributor to all of the six environmental impact categories, accounting for more than 95% of the total value, respectively. These impacts are mainly attributed to the production of the cathode active material

(NCM 622), wrought aluminum and DMC. For POCP and HTP, the contribution from the material preparation stage takes account of around 200%, largely due to the production of wrought aluminum. The contribution of the production stage is relatively lower than the material preparation stage, accounting for 20.3% of the total GWP, 12.8% of the total PED and 9.2% of the total AP, 7.0% of the total POCP, around 2% of the total EP and HTP, respectively. In the production stage, cell manufacturing is the main contributor (around 95%) for all six impact categories due to the high energy consumption. For all six impact categories, the end-of-life stage contributions are negative. Waste NCM 622 battery recycling in the end-of-life stage can reduce 0.03 kg C_2H_4 e (105.2%) of the life cycle POCP and 41.6 kg 1,4-DB e (139.8%) of the life cycle HTP, mainly because of the recycling of waste wrought aluminum. Besides, waste NCM 622 battery recycling could also reduce 30.9 kg CO_2 e (33.0%) of the life cycle GWP and 158.3 MJ (14.7%) of the life cycle PED, due to the reproducing of NCM 622. The life cycle assessment results for per kg NCM 622 battery are shown in Table S 7 in the Supporting Information.

Table 2 presents the LCIA results of 10 types of impact categories by using the ReCiPe Midpoint (H) V1.11 / World Recipe H RECIPE method. It is found that the results of GWP, AP, POCP, EP and HTP are similar to those assessed by the CML-IA baseline V3.02 method.

Table 2 Life cycle assessment results for per kWh NCM 622 battery (ReCiPe Midpoint (H) V1.11/ World Recipe H)

Impact category	Unit	Material	Production	End-of-life	Total
Climate change (GWP)	kg CO_2 eq	105.47	19.01	-30.91	93.57
Terrestrial acidification (AP)	kg SO_2 eq	0.47	0.05	-0.03	0.49
Photochemical oxidant formation (POCP)	kg NMVOC	0.34	0.04	-0.09	0.29
Freshwater eutrophication (EP)	kg P eq	0.01	0.00	0.00	0.01
Marine eutrophication (EP)	kg N eq	0.13	0.00	-0.11	0.02
Human toxicity (HTP)	kg 1,4-DB eq	26.01	0.61	-14.09	12.53
Terrestrial ecotoxicity	kg 1,4-DB eq	0.03	0.00	-0.02	0.01
Freshwater ecotoxicity	kg 1,4-DB eq	21.43	0.00	-19.93	1.5
Particulate matter formation	kg PM10 eq	0.15	0.01	-0.01	0.15
Metal depletion	kg Fe eq	6.06	0.00	1.73	7.79
Fossil depletion	kg oil eq	24.67	3.12	-3.65	24.14

4.2 Identification of significant environmental impacts

Figure 4 presents the relative contributions in the material preparation stage of 1 kWh NCM 622 battery. For the PED and GWP, the cathode active material (NCM 622) and wrought aluminum are the top two contributors, together accounting for around 75% of the battery materials. 60% of the AP, more than 40% of the PED and GWP is contributed by the NCM 622. Wrought aluminum is the most substantial contributor to the POCP and HTP, accounting for more than 60% and 70% of the battery materials, respectively. For the EP, however, the predominant contributor is the electrolytes DMC (73.3%), followed by NCM 622 (15.4%). Graphite contributes 10.8% for the PED, 6.9% for the GWP, 4.2% for the AP and less than 2% in the other three impact categories in the material preparation stage. For all the six impact categories, copper, $LiPF_6$ and electronic parts account for less than 4%, 7% and 7% of the battery materials, respectively.

Figure 5 shows the relative contributions in the production stage of 1 kWh NCM 622 battery. Vacuum drying process accounts for the largest proportion (more than 40%) for all the six environmental impact categories, followed by the coating and drying (around 36%), due to the large share of the energy demand in these two processes. Formation contributes to 10%~15% for the six environmental impact categories. The mixing process and module and pack assembly process account for less than 5% for the six environmental impact categories, respectively.

4.3 Comparative analysis

We compare the GHG emissions of NCM battery production (material preparation and production) with existing literature studies in Figure 6. The total GHG emissions are disaggregated and associated with cell materials, battery components, cell manufacturing, module and pack assembly and others. Figure 6 reports great variation in the overall production GHG emissions with results ranging between 73 and 200 kg CO_2 e/kWh, showing different contributions from cell materials, battery components, cell manufacturing and module and pack assembly. The result for NCM battery production GHG emissions in this study is 124.5 kg CO_2 e/kWh, which is similar to that reported by USEPA (2013). The production GHG emissions determined by MajeauBettez et al. (2011) where inventory data from Ecoinvent 2.2 database were used are nearly two times higher than this study. They based their energy data on industry reports published nearly 15 years ago, at their early commercialization stage, therefore it might not reflect current NCM battery production practices (Dai et al., 2019; Rydh and Sandén, 2005). It seems that Ellingsen et al. (2014) and Kim et al. (2016) where inventory data from Ecoinvent 3.1 database were used overestimated the energy consumption during the cell manufacturing process, which are more than three times higher than those in this study. The GHG emissions of the plant in the study of Ellingsen et al. (2014) and the underutilization of the plant in the study of Kim et al. (2016) would lead to the overestimation of energy intensity for cell production (Dai et al., 2019). The GHG emissions for cell manufacturing of this study (NCM 622) is similar with those of the study of Dai et al.

(2019) (NCM 111), because the energy consumption data of this process are both based on Chinese factories. The GHG emissions for cell materials of this study is much higher than Dai et al. (2019) where inventory data were also supplemented by GREET model, as our study is for NCM 622 which represents the state-of-art technology in China, while Dai et al. (2019) analyzed NCM 111 which represents the old-fashioned technology in China. The proportion of GHG emissions in the module and pack assembly is less than 1% for all the studies except MajeauBettez et al. (2011) (3%).

4.4 **Sensitivity analysis**

As shown in the section 4.1, the material preparation stage is the primary contributor to all the six environmental impact categories, especially for the cathode active material, NCM622. The current trend of NCM battery technology is to replace NMC622 by NMC811. Therefore, the sensitivity analysis is performed to evaluate the impacts of replacing NMC622 by NMC811. Based on expert consultation, the mass of cathode active material and battery energy density of the LIB are assumed to be not change despite the changes of the cathode active material chemistry . The sensitivity analysis results show that the total life cycle GWP, AP and POCP could be increased by around 1%, while the total life cycle PED, EP and HTP could be increased slightly by less than 0.3%. This is primarily because the increased content of $NiSO_4$ in the production of NCM 811 Precursor results in increased consumptions of steam, LiOH and oxygen for the final production of NCM 811 relative to per kg of NCM 622 (see Table S 2 and S 3 in the Supporting Information).

5 Conclusions

In this study, the environmental impacts of the most commonly used NCM 622 battery for passenger BEVs in China were assessed throughout the life cycle. Primary data were collected from two Chinese leading LIB suppliers (world’s top three), two leading cathode material producer (world’s top five), and two battery recycling corporations (one is owned by the world’s top three LIB supplier, and the other one is the world's leading waste battery and cobalt nickel tungsten rare metal recycling corporation) from 2017 to 2019. The evaluation is presented in terms of six impact categories following the CML-IA baseline V3.02 method: primary energy demand (PED), global warming potential (GWP), acidification potential (AP), photochemical oxidant creation potential (POCP), eutrophication potential (EP), and human toxicity potential (HTP). The study results can be listed as follows.

Firstly, the material preparation stage is the largest contributor to all the six environmental impact categories, largely due to the production of the cathode active material (NCM 622), wrought aluminum and electrolytes. The contribution of the production stage is relatively lower than the material preparation stage. Waste LIB recycling in the end-of-life stage could largely reduce the life cycle POCP and HTP of LIB, mainly because of the recycling of waste wrought aluminum. Secondly, in the material preparation stage, the battery cell materials, including the cathode active material and wrought aluminum are the predominant contributors to the PED and GWP. Wrought aluminum is the most substantial contributor to the POCP and HTP, while the electrolytes are the predominant contributor to the EP. Besides, electronic makes a considerable contribution to the HTP. In the production stage, vacuum drying and coating and drying processes are the top two contributors. Finally, from the sensitivity analysis, replacing NMC622 by NMC811 as the cathode active material could increase all the six environmental impacts.

However, the use stage is not included in the NCM 622 battery's system boundaries due to the large uncertainty of some key parameters, such as the real world driving cycles, different charging behaviors, battery replacement times, and the lack of unified allocation method of the electricity consumption of the battery pack. Therefore, when considering the whole LIB life cycle, it could cause quite different results for different impacts when including the use stage which shall be evaluated in the future studies when the key information is available. In order to better perform LIB eco-design, future LIB technologies should also emphasize by optimizing of the cathode active material with the preference on the impacts of different life cycle stages.

In addition, with the progress of LIB technology, continued environmental LCA efforts combined with the cost analysis based on primary data, especially for the recycling stage, are necessary to provide efficient strategies for full life cycle environmental impact reduction in LIBs and the whole value chain in sustainable development of BEVs.

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Conflicts of interest

None.

Nomenclature

Name	Abbreviation
Acidification potential	AP
Battery electric vehicles	BEVs
China automotive life cycle database	CALCD
Dimethyl carbonate	DMC
Ethylene carbonate	EC
Eutrophication potential	EP
Fuel cell electric vehicles	FCVs
Global warming potential	GWP
Human toxicity potential	HTP
Life cycle assessment	LCA
Life cycle inventory	LCI
Lithium iron phosphate	$LiFePO_4$, LFP
Lithium manganese oxide	$LiMn_2O_4$, LMO
Lithium nickel cobalt manganese oxide	$LiNi_xCo_yMn_zO_2$, NCM
Lithium-ion power batteries	LIBs
Lithium-ion power battery	LIB
New energy vehicles	NEVs
Photochemical oxidant creation potential	POCP
Plug-in hybrid electric vehicles	PHEVs
Polyvinylidene fluoride	PVDF
Primary energy demand	PED

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Figure captions

Figure 1 System boundaries of NCM 622 batteries excluding use phase

Figure 2 Material compositions of per kWh NCM 622 battery

Figure 3 Life cycle assessment results for per kWh NCM 622 battery (CML-IA baseline V3.02)

Figure 4 Relative contributions of per kWh NCM 622 battery material

Figure 5 Relative contributions of per kWh NCM 622 battery production

Figure 6 GHG emissions of per kWh NCM battery production

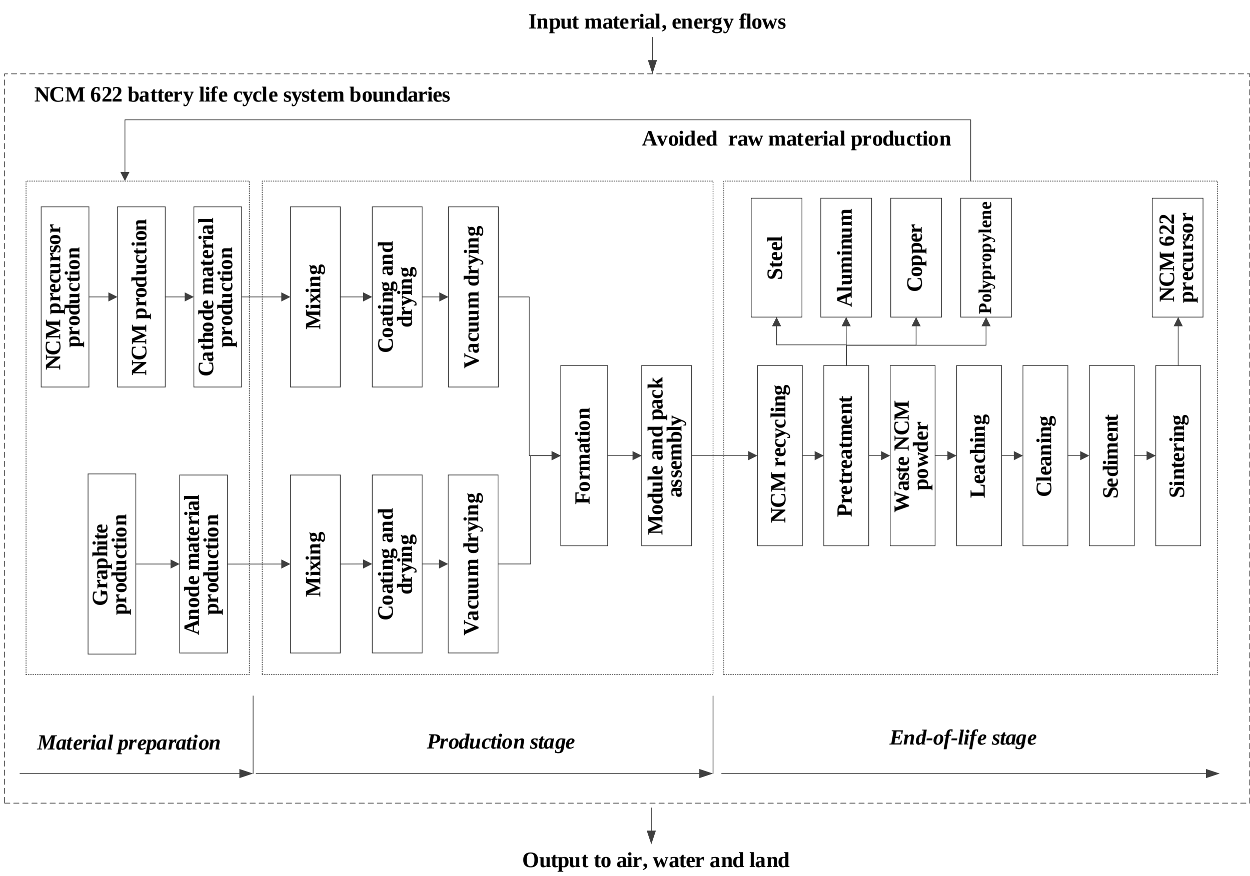

Figure 1 System boundaries of NCM 622 batteries excluding use phase

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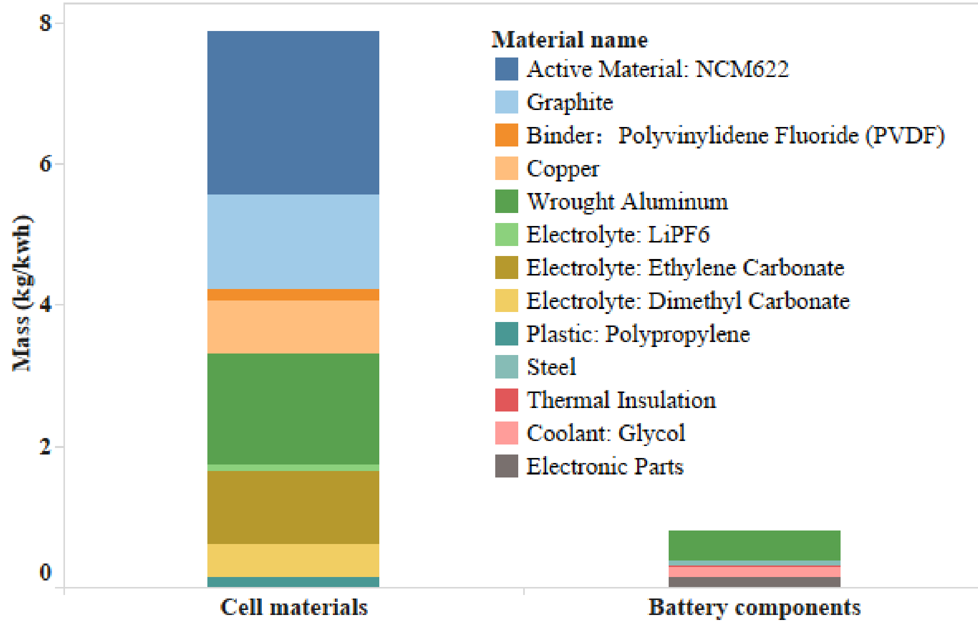

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392 Figure 2 Material compositions of per kWh NCM 622 battery. The material masses per kWh is calculated by (pack

393 energy density × the material mass percentage of the pack) ×1/1000

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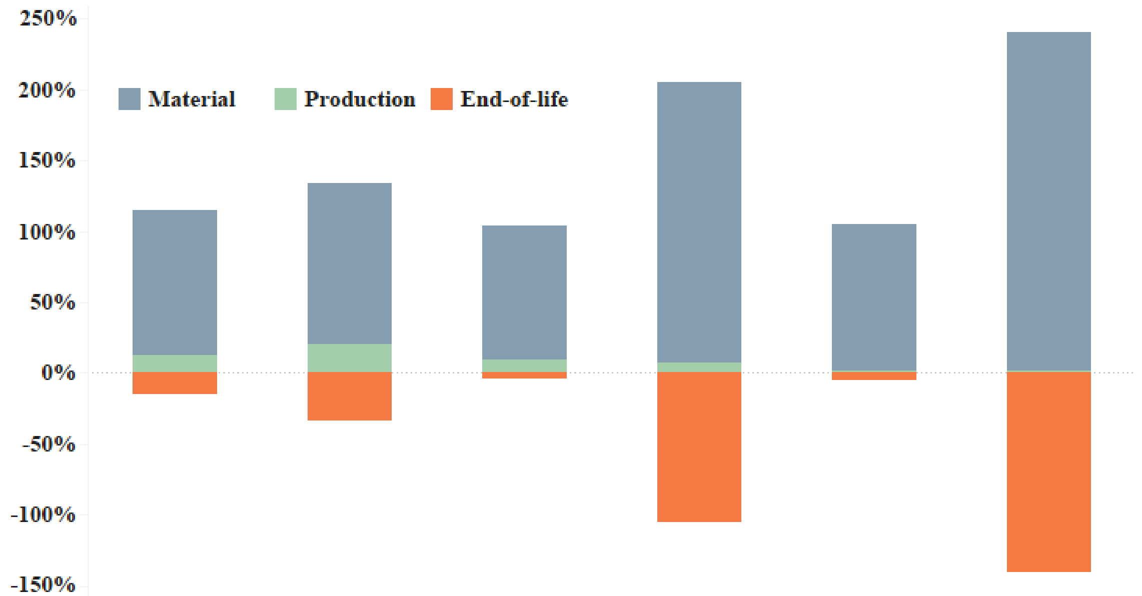

Life cyle stage	PED (MJ)	GWP (kg CO2 e)	AP (kg SO2 e)	POCP (kg C2H4 e)	EP (kg PO43- e)	HTP (kg 1,4-DB e)
Material	1,097.80	105.47	0.51	0.05	0.24	70.79
Production	137.51	19.01	0.05	0.00	0.00	0.56
End-of-life	-158.29	-30.91	-0.02	-0.03	-0.01	-41.60
Grand Total	1,077.01	93.56	0.54	0.03	0.23	29.75

Figure 3 Life cycle assessment results for per kWh NCM 622 battery (CML-IA baseline V3.02)

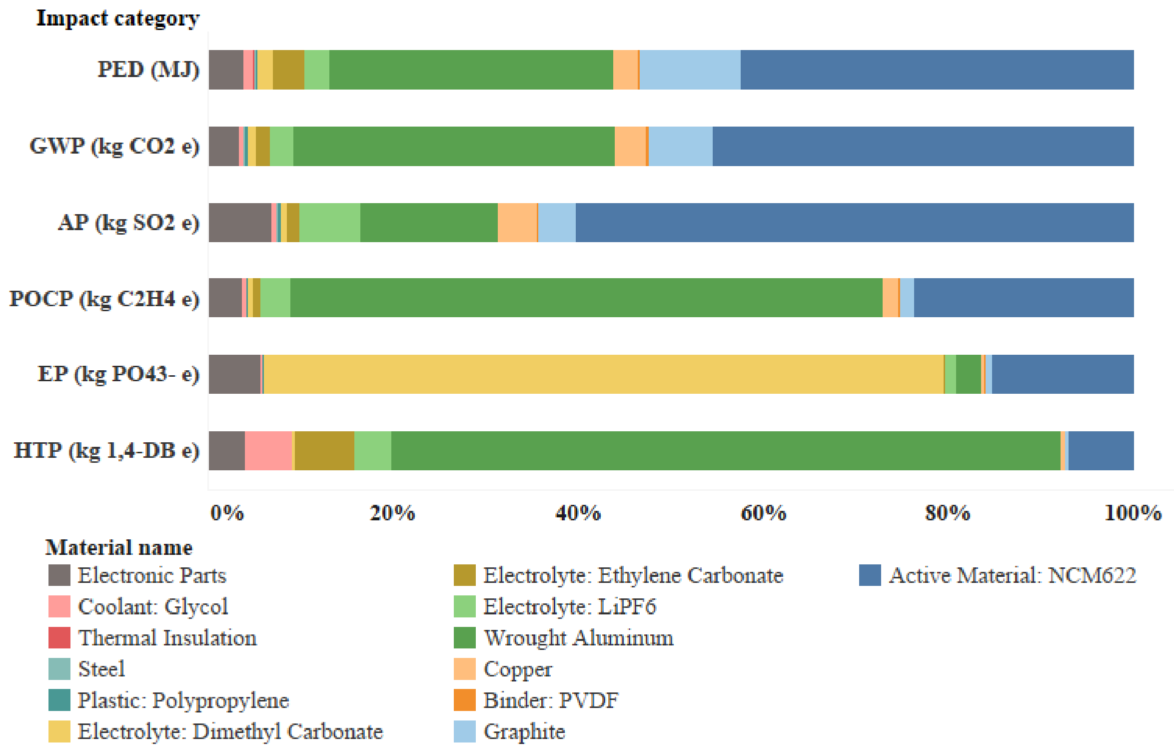

Figure 4 Relative contributions of per kWh NCM 622 battery material

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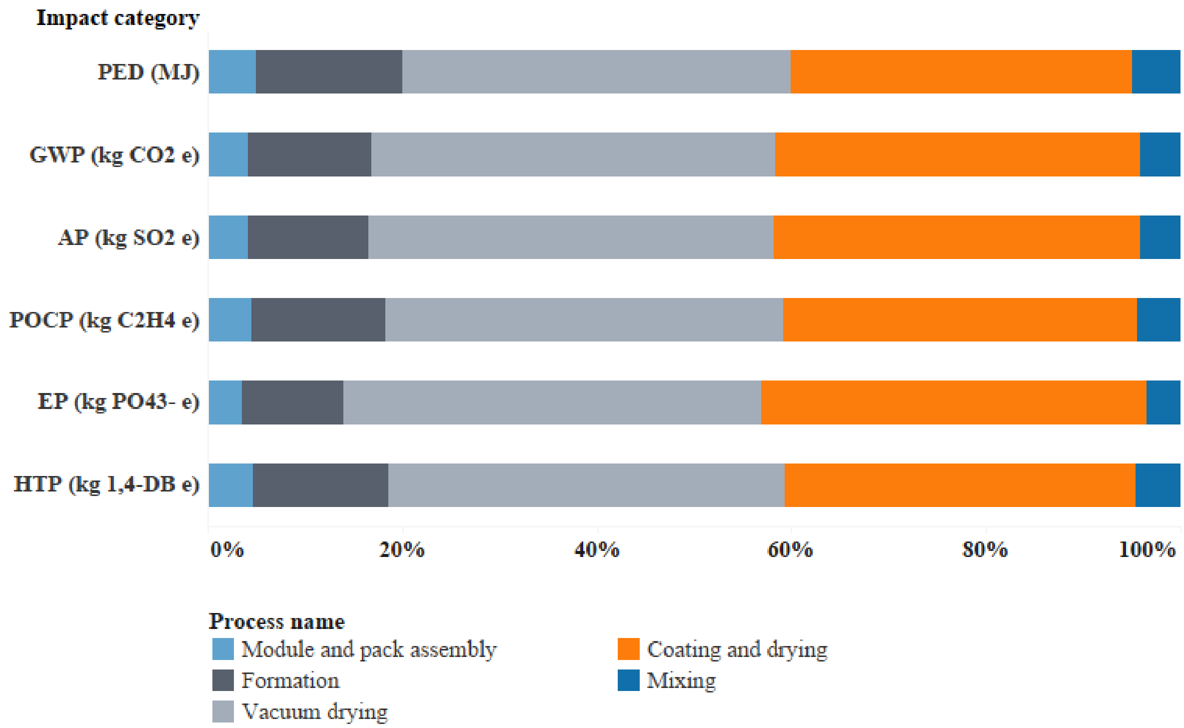

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404 Figure 5 Relative contributions of per kWh NCM 622 battery production

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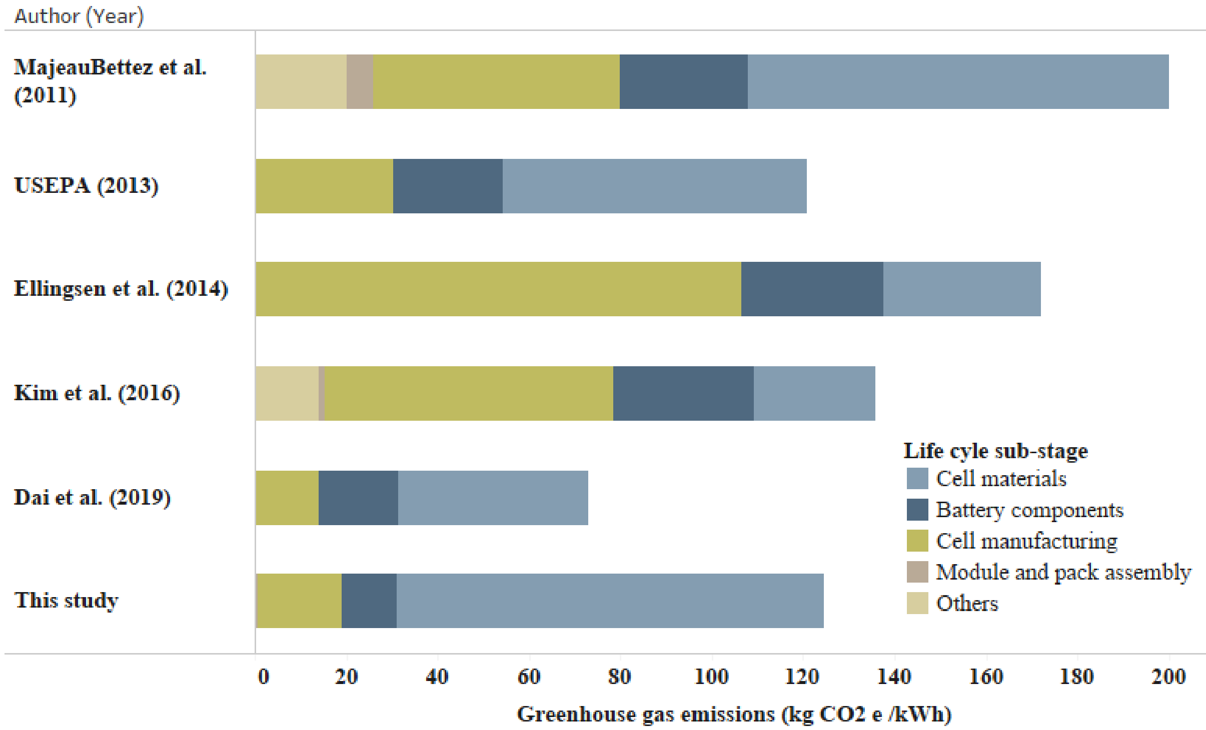

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407 Figure 6 GHG emissions of per kWh NCM battery production