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Research paper

Life-cycle assessment of the environmental impact of the batteries used in pure electric passenger cars

Xiong Shu [a,b], Yingfu Guo [a], Wenxian Yang [c], Kexiang Wei [b,*], Guanghui Zhu [d]

[a] *School of Mechanical Engineering, Hunan University of Science and Technology, Hunan, Xiangtan, 411201, China*
[b] *Hunan Provincial Key Laboratory of Vehicle Power and Transmission System, Hunan Institute of Engineering, Xiangtan, 411104, China*
[c] *School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK*
[d] *Technology Center of Xiangtan Electric Manufacturing Group, Hunan, Xiangtan, 411201, China*

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ABSTRACT

The use of electric vehicles is for reducing carbon emissions, thereby reducing environmental pollution caused by transportation. However, the large-scale production and application of electric vehicle batteries have brought another notable issue, i.e., the production and application of these batteries also cause environmental pollution. Particularly, the precious metal materials used in the batteries are harmful to human health and the surrounding ecological system. Nowadays, many types of batteries are available. It is essential to understand which of them is most suitable for electric vehicles from the perspective of environmental protection. To answer this question, the life cycle environmental impact assessment of $LiFePO_4$ battery and $Li(NiCoMn)O_2$ battery, which are being popularly used in pure electric passenger vehicles, are conducted in this paper. The research has shown that the two types of batteries show different environmental impact features in different phases. For example, $LiFePO_4$ batteries are more environmentally friendly in the phase of production, while $Li(NiCoMn)O_2$ batteries are more eco-friendly in the application and transportation phases. Despite this, $LiFePO_4$ batteries are generally more environmentally friendly than $Li(NiCoMn)O_2$ batteries from the perspective of the entire life cycle. In addition, the research results also suggest that due to the heavier mass, $LiFePO_4$ batteries can probably gain more benefit when used for energy storage.

1. Introduction

Electric vehicles (EVs) are considered to be carbon-free, which helps to slow climate change, improve public health, and reduce ecological damage. Coupled with the increasing pressure to achieve the net-zero target, the global EV market has taken a huge leap forward in the past decade (Du et al., 2017). In 2019, the number of light EVs globally reached 2,264,400 units, which is 9% higher than in 2018. Take the world's largest EV market, China, as an example, only 5,000 EVs were sold in the Chinese market in 2011. In 2018, China sold 984,000 pure EVs, which was an increase of 50.8% over the previous year (China Association of Automobile Manufacture, 2019). In 2019, more than 1 million EVs were sold in China, and the stock of EVs reached 3.8 million (Sun et al., 2020). These data imply that there will be more and more EVs running on the road in the following years.

Since batteries are the only source of power for EVs, the globally booming EV market means that a huge number of Lithium-ion power batteries (LIBs) will be produced, used, and disposed of in the future (IEA, 2020). For example, the cumulative installed capacity of LIBs reached about 206 GWh in China by the end of 2019 (MIIT, 2019). Among these LIBs, $LiFePO_4$ batteries and $Li(NiCoMn)O_2$ batteries dominate the market, but their market shares changed over time. The market shares of $LiFePO_4$ batteries, $Li(NiCoMn)O_2$ batteries, and lithium titanate (LTO) batteries were respectively 28%, 18%, and 21% before 2016 (MIIT, 2019). Since 2016, the market share of $Li(NiCoMn)O_2$ batteries increases rapidly. During the period from 2016 to 2018, more than 80% of electric passenger cars in China used $Li(NiCoMn)O_2$ batteries. This situation changed again in 2019 when manufacturers favored using $LiFePO_4$ batteries to power electric passenger cars.

The changes in the market shares of different types of EV batteries over time are motivated by a variety of reasons, such as the pursuit of higher safety, higher energy density, better charge–discharge performance, and so on. Among these motivations, the pursuit of more environmentally friendly products should be one of the most important motivations. This is because the original intention of using EVs is to reduce carbon emissions and mitigate environmental pollution caused by transportation. However, the LIBs are made of multiple kinds of metal materials, e.g. nickel, chromium, and manganese constitute the precursor materials of

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[*] Corresponding author.
E-mail address: kxwei@hnie.edu.cn (K. Wei).

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the $Li(NiCoMn)O_2$ batteries. These metal materials can generate pollutants in the process of material exploitation, battery production, and battery recycling or disposal. Studies have shown that a button battery can pollute 600,000 liters of clean water, and a D-size battery that rots underground can pollute a square meter of land (MIIT, 2019). Hence, the large-scale production and usage of EV batteries have brought a notable issue, i.e. the production, application, and recycling/disposal of these EV batteries can cause environmental pollution as well. Nowadays, many types of batteries have been developed for EVs. They are distinctly different in materials, manufacturing process, production process, and recycling/disposing method, thereby having a different impact on the environment (Du et al., 2017). Then, which of them is the best for the EVs has become an interesting question.

To answer this question, much effort has been made in the past years. For example, the life-cycle assessment (LCA) study of LMO batteries and the contributions to the environmental burden caused by different battery materials were analyzed in Notter et al. (2010). The LCA of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles was conducted in Sun et al. (2020). It was found that the material exploitation stage is the biggest contributor to energy consumption, global warming potential, and acidification potential. Kim et al. (2016) chose a commercial BEV and assessed the life cycle greenhouse gas (GHG) emissions and other air emissions of traction batteries. The environmental impacts of next-generation LIBs compared with conventional LIBs to support the selection and development of future LIBs were reported in Li et al. (2014) and Deng et al. (2017). A review of LCA studies on LIB was conducted in Peters et al. (2017) and it was found that only a few publications provided original life cycle inventory (LCI) data. The 'cradle-to-gate' environmental impacts of NCM batteries was also conducted in Ellingsen et al. (2014) using midpoint indicators. The "cradle-to-gate" emissions assessment of a mass-produced EV battery done in Khatri et al. (2017) disclosed that the greenhouse gas was emitted mainly during the production of battery cells. The environmental impact of different types of EV batteries in the production phase was also studied by scholars. To name a few, the environmental impacts of NCM batteries, NiMH batteries, and $LiFePO_4$ batteries in the production phase were compared in MajeauBettez et al. (2011) and it was found that NiMH batteries have the highest environmental burden in the production process. Similar work was also reported in Olofsson and Romare (2013), Dunn et al. (2010). Besides, many other studies were also conducted before from different perspectives to investigate the environmental impact of EV batteries. For example, the environmental impact of $LiFePO_4$ batteries when produced using different solvents was studied in Zackrisson et al. (2010). The results suggested that water was better than N-methyl-2-pyrrolidone (NMP) when used as the solvent to produce $LiFePO_4$ batteries. Many similar kinds of research also can be found in the existing literature. The "cradle-to-gate" energy consumption, gas emissions (SO_x, NO_x, CO_2), and water consumption during the production of NCM batteries were investigated in Chen et al. (2019), Dai and Kelly (2019); The energy consumption and air pollution during the recycling process of $LiMn_2O_4$ batteries were studied in Dunn et al. (2012); the recycling methods of different types of batteries were analyzed in Hendrickson et al. (2015) and it was found that hydrometallurgical method was more energy effective than pyrometallurgical method. In addition, the research in Marques et al. (2019) disclosed that the environmental impact of EV batteries also depends on the usage scenario.

In summary, the environmental impact of EV batteries has been studied before by many scholars, but they presented significantly different results with large uncertainties associated with data and results. Firstly, most of these studies used disunified LCI databases or literature publications as data sources. In addition, for the foreground data, most studies were conducted based on previous and did not reflect the current commercial-scale automotive LIB production (Sun et al., 2020). Furthermore, almost all existing studies focus on investigating the environmental impact of the EV batteries only in individual phases, few of them provide a global view of the environmental impact of the batteries throughout their life cycle. However, the environmental impact of EV batteries is a very complex issue, not only affected by material exploitation and battery manufacturing and production methods, but also by battery transportation, usage, recycling, or disposal methods (Wang et al., 2020; Zhiyong et al., 2020; ISO, 2006a). The purpose of this research is to fill this knowledge gap by studying the life-cycle environmental impact of the two most commonly used EV LIBs, namely $LiFePO_4$ batteries and $Li(NiCoMn)O_2$ batteries. In the study, the data used for the environmental impact assessment in the battery production and recycling phases are from leading LIB suppliers, while the data used for the environmental impact assessment during the battery application phase are from the durability tests conducted under New European Driving Cycle (NEDC). It is believed that this study is a good complement to the current research of EV batteries and the outcome will benefit the optimal application of the two types of batteries of interest.

2. Methodology

Due to $LiFePO_4$ batteries and $Li(NiCoMn)O_2$ batteries the most commonly used batteries in EVs today, the two types of batteries of the same capacity of 28 kWh are considered in this paper. In the study, it is assumed that the service life of the electric passage car is 200,000 km. Due to the usage scenario will affect energy consumption, capacity fading of the batteries, and the number of batteries required in the service life of the EV, the details of the experimental data and testing method are introduced in Section 2.4. To ensure the reliability of the research result, the assessment will be conducted by following the International Standard ISO 14040 (ISO, 2006b; Hua et al., 2020) and with the aid of commercial software SimaPro 9.0.

2.1. LIBs and system boundaries

Generally, the cells in EV LIBs system can be designed and manufactured into different shapes and sizes. However, from the point of view of structure and composition, a battery generally consists of an anode, a cathode, copper foil, electrolytes, separators, etc. Because the capacity, voltage, and discharge power of a single battery cell are very limited, in practice, hundreds of battery cells are often connected in series and parallel to form a powerful battery system to drive an EV. Generally, a battery system includes battery modules, battery management systems, wiring harnesses, fuses, relays, etc. The functions of these subsystems have been explained in detail in Shu et al. (2020).

The system boundaries for the LCA of EV batteries are shown in Fig. 1. They define the scope of this study, which covers the production of components and battery cells, the assembly of LIB, the usage of LIBs in electric passenger cars, and the recycling/disposal of LIBs. However, the production and recycling of the other parts of EVs are not considered because they are unrelated to the environmental impact assessment of the power batteries.

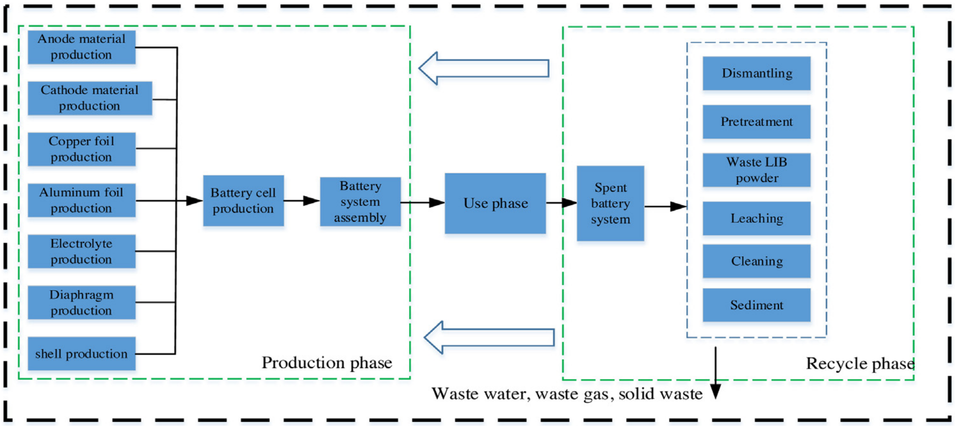


Fig. 1. System boundaries for the LCA of the batteries of interest.

(a) The electric passenger car of interest (b) Battery cells of Li(NiCoMn)O_2 (c) Battery system of Li(NiCoMn)O_2

(d) Battery cells of $LiFePO_4$ (e) Battery system of $LiFePO_4$

Fig. 2. Electric passage car and its battery system.

2.2. The battery system of electric passenger cars

To ease understanding, the pure electric passenger car of interest is shown in Fig. 2. Its maximum speed is 120 km/h; and the maximum speed and power of its drive motor are 9500 rev/min and 35 kW, respectively. Other powertrain system parameters of this type of electric passenger car are listed in Table 1.

Due to the continuous evolution of products, some of these types of electric passenger cars are equipped with $LiFePO_4$ battery systems, but others are equipped with Li (NiCoMn) O_2 battery systems. Both systems have the same battery capacity but different weights and specifications. The working parameters of the two types of battery systems are listed in Table 2.

From Table 2, it is clearly seen that for $LiFePO_4$ battery system and Li(NiCoMn)O_2 battery system with almost the same power capacity (i.e. the former is 28.20 kWh and the latter is 28.01 kWh), The energy density of Li(NiCoMn)O_2 battery system (200 Wh/kg) is much higher than the energy density of $LiFePO_4$ battery system (155 Wh/kg). The mass ratios of different components in the 1 kWh $LiFePO_4$ battery system and 1 kWh Li(NiCoMn)O_2 battery system (i.e. LIBs PACK) are listed in Table 3 for comparison.

From Table 3, it is seen clearly that the mass ratios of all items (e.g., anode, copper foil, aluminum foil, diaphragm, etc.) in the two types of batteries are quite similar.

2.3. The phase of production

The battery system is produced in two steps. The first step is the production of battery cells, and the second step is the assembly of the battery system (Ellingsen et al., 2013). In this study, the battery cells used for building the two types of battery systems are respectively the L48 Li(NiCoMn)O_2 battery cell and the PH80AH $LiFePO_4$ battery cell. Both are mainstream battery cell products and are widely used in pure electric passenger vehicles today. The manufacturing process of the cathode materials used in Li(NiCoMn)O_2 battery cells and $LiFePO_4$ battery cells are shown in Fig. 3.

In the process of manufacturing a battery system, the raw materials should be prepared first. Then, use these raw materials to manufacture and produce the battery cells. Finally, the battery cells, electronic devices, copper bars, battery management systems, etc., are assembled together to form a battery system. In the

Table 1
Powertrain system parameters of the electric passenger car.

Item	Parameters	Item	Parameters
Length–width–height (mm)	3560–1610–1705	Wheelbase (mm)	1360/1370
Minimum ground clearance (mm)	≧185	Maximum speed (km/h)	120
Curb quality (kg)	950	Maximum total mass (kg)	1010
Tire specifications	205/70 R15	Wheelbase (mm)	2250
Motor type	Permanent magnet synchronous motor	Controller capacity (KVA)	60
Maximum output power (kW)	35	Maximum working voltage (V)	400 V
Peak speed (rpm)	9500	Controller output frequency range (Hz)	0∼600
Peak torque (Nm)	140	Peak point current (A)	300
Nominal voltage (V)	AC227	Controller nominal voltage (V)	DC350

Table 2
Working parameters of the two types of battery systems.

Battery chemistry	$LiFePO_4$ battery	$Li(NiCoMn)O_2$ battery
Cell rated voltage (V)	3.2	3.65
Operating voltage range (V)	2.5–3.7	2.85–4.18
Rated capacity (Ah)	80	80
Temperature of operation (°C)	0–50	0–50
Relative humidity (%)	2–85	2-85
Cell energy density (Wh/kg)	155	200
Rated voltage of battery system (V)	352	350
Operating voltage range of battery system (V)	275–407	273–401
Maximum allowable charge current (A)	48	49
Energy density of battery system (Wh kg-1)	121	149
Power of the battery system (kWh)	28.20	28.01
Weight (kg)	232.5	184.7

Table 3
The mass ratios of different components in the two types of 1 kWh battery systems.

Item	$LiFePO_4$	$Li(NiCoMn)O_2$	Applied to	Item	$LiFePO_4$	$Li(NiCoMn)O_2$	Applied to
Cathode	25.2%	26.8%	Cell	Electrolyte	13.2%	10.7%	Cell
Anode	15.3%	15.5%	Cell	Polypropylene	4.6%	4.2%	Cell
Carbon black	2.1%	2.4%	Cell	Steel	2.2%	2.7%	Battery
Binder: PVDF	3.4%	3.2%	Cell	Thermal insulating material	1.3%	1.2%	Battery
Copper foil	12.8%	12.9%	Cell	Electronic components	0.6%	0.7%	Battery
Aluminum	18.3%	18.1%	Cell & battery	Polyethylene	0.3%	0.5%	Battery

(a) Manufacturing of cathode material used in $Li(NiCoMn)O_2$ battery cell

(b) Manufacturing of cathode material used in $LiFePO_4$ battery cell

Fig. 3. The manufacturing process of cathode materials in two types of batteries.

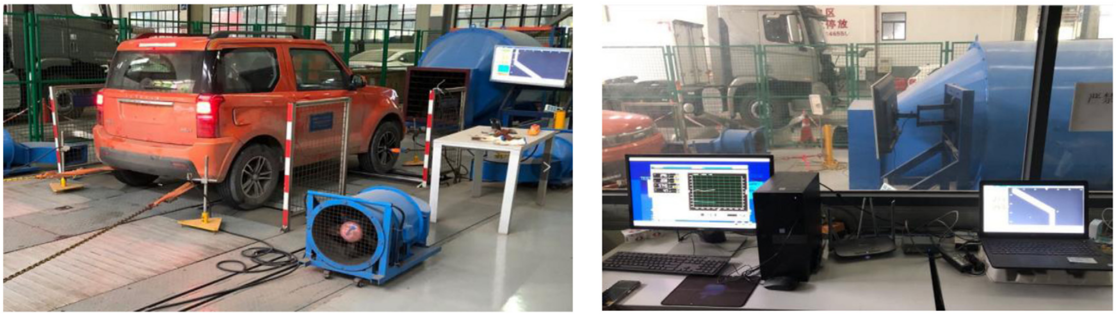
study, the primary inventory data and the energy consumption data are from a Chinese leading LIB supplier. These data are based on a cell production capacity of nearly 8 GWh/yr. The detailed inventory data are listed in Tables A.1–A.6 in Appendix. Other raw material data for cell production are from the European Reference Life Cycle Database (ELCD).

2.4. The phase of usage

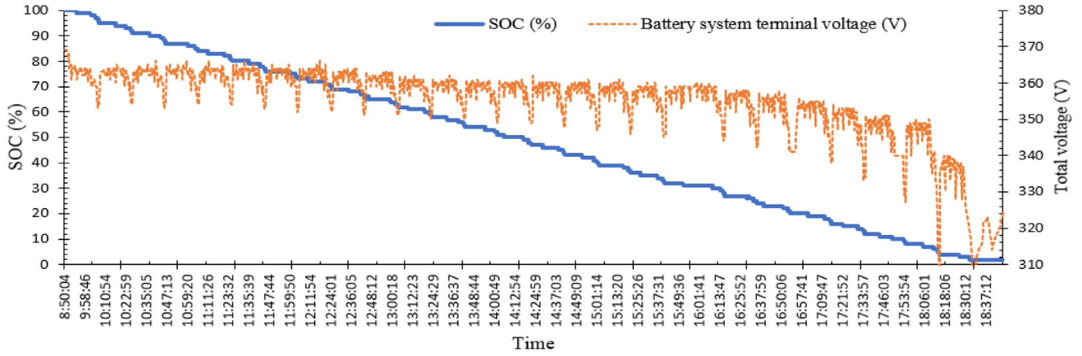
When assessing the environmental impact of the EV batteries in the phase of usage, not only the actual energy consumption of the EV but also the fading feature of battery capacity over time will be considered.

Since many factors (e.g., road conditions, environments, the driver's driving habits, etc.) can significantly affect the energy consumption of the EVs, the actual recharge mileage of the vehicle and the service life of the battery may vary within a large range. In order to achieve a reliable assessment of the two types of EV batteries of interest, the cruising range of the vehicle is usually tested in the lab under the NEDC (JianqinFu et al., 2018). To ease understanding, the setup for testing the energy consumption of the pure electric passenger car under the NEDC is shown in Fig. 4. In the electric vehicle energy consumption test system, the test bench (Fig. 4a) contains drum motor and its drive system; the control system includes the NEDC working condition file import system, the drum speed control system, the data record storage system, the emergency stop system and the human–computer interaction system, etc.

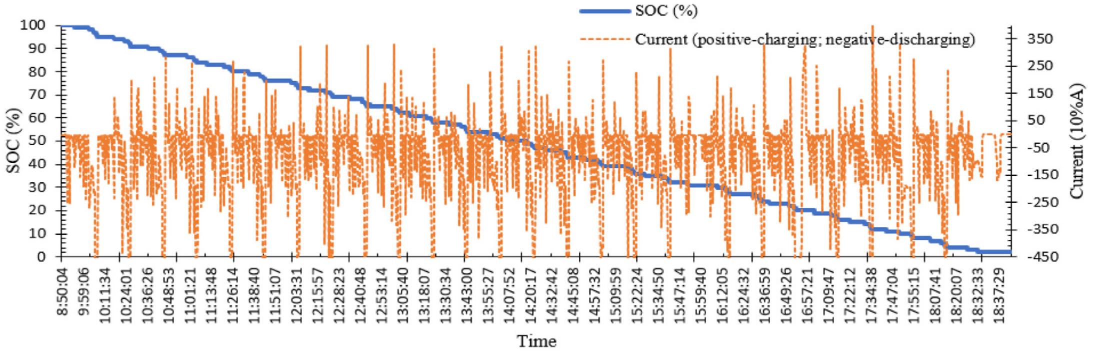
It is time-consuming to perform the energy consumption test of pure electric passenger cars under the NEDC. In the example shown in Fig. 4, it took about 520 min to complete the test.



(a) Test bench (b) Control system ()



(c) State of charge (SOC) and the variation of voltage during the testing process



(d) State of charge (SOC) and the variation of current during the testing process

Fig. 4. Energy consumption test under the NEDC.

In the testing process, the electric passenger car being tested is requested to run by repeatedly following the simulated urban and extra-urban driving cycles defined in the NDEC. Since it usually needs 1180 s to complete a standard NEDC corresponding to a mileage of 11.03 km, the periodic changes in the terminal voltage and output current of the battery system can be respectively observed from Figs. 4c and 4d. Correspondingly, it is found that the SOC of the battery system gradually decreases over time with the increase of mileage. Apparently, from the testing results shown in Fig. 4, one can readily understand the energy consumption and discharge current of the electric passenger vehicle in the phase of usage.

By using the method depicted above, an electric passenger car was tested in this study. The test results show that when the car is equipped with a $LiFePO_4$ battery system, the total cruising range is 261 km, and when the car is equipped with a $Li(NiCoMn)O_2$ battery system, the total cruising range is 278 km. Since the power capacity of the $LiFePO_4$ battery system is 28.20 kWh and the power capacity of the $Li(NiCoMn)O_2$ battery system is 28.01 kWh, it is readily known that the energy consumption of the car is respectively 9.2553 km/kWh and 9.9250 km/kWh when it is equipped with a $LiFePO_4$ battery system and a $Li(NiCoMn)O_2$ battery. From these calculation results, it can be concluded that the car can travel farther when it is equipped with a $Li(NiCoMn)O_2$ battery system. This is because the capacity density of $Li(NiCoMn)O_2$ battery system is higher than that of $LiFePO_4$ battery system, i.e. the $Li(NiCoMn)O_2$ battery system is lighter than the $LiFePO_4$ battery system with the same power capacity.

Capacity fade is usually used to determine the number of batteries needed to fulfill the service life of the electric passenger car. Regarding the end service life of the battery, the United States Advanced Battery Consortium (USABC) recommends that the battery should be replaced when the battery capacity reaches 80% (Tong et al., 2013). Many EV factories around the world implement the scrap index of EV batteries based on this recommendation. So, this recommendation is also accepted in this study as the battery scrap index of electric passenger vehicles.

Table 4
Energy consumption in the phase of usage of the two types of battery systems.

Items	$LiFePO_4$	$Li(NiCoMn)O_2$
Total car mass M_v (kg)	1,010	962
Total capacity of electric passage car (kWh)	28.16	28.01
Range of electric passage car (km)	261	278
Number of cycles for capacity decay to 80%	2101	1673
The total electrical energy input from the grid when the battery system capacity decays to 80%	45,374	44,166
Total energy transferred when the battery system capacity decays to 80% (kWh battery-1)	40,950	39,860
Total efficiency of motor system and mechanical transmission	90%	90%
The energy used by the motor system to do work when the battery system capacity decays to 80% (kWh)	36,855	35,874
Power consumption per unit distance (km/kWh)	9.255	9.925
Average power consumption per unit distance (kWh/km)	0.108	0.101
Total distance traveled when the battery system capacity decays to 80% (km battery system-1)	341,093.0	356,049.5
Number of batteries required for 200,000 km service life	0.586	0.562
The total electrical energy input from the grid when the passage car services life is 200,000 km (kWh)	26,589.2	24,821.3

In real-life, degradation may happen on the capacity of EV LIBs, depending on many factors, such as the discharge depth of the battery, discharge rate, ambient temperature, pack structure of the battery system, and the control strategy of the battery management system. To estimate the degradation and the actual capacity of the battery over time, much effort has been made and many methods have been developed. For example, battery degradation was studied in Waag et al. (2014) by considering the dynamic parameters, thermodynamic parameters, and electrical properties of the battery materials; An electrochemical model was established in Safari and Delacourt (2011) for simulating the growth of SEI membranes and the effect of SEI membranes on the degradation of battery capacity; A systematic study was also conducted in Su et al. (2016) to investigate the battery degradation by considering seven factors and based on the investigation results an empirical aging model was established. Besides, to predict the State of Health (SOH) of LIBs, the BP neural network and Fuzzy logic algorithm were respectively adopted in Pan et al. (2018) and IL-Song (2010) to construct the prediction model. There is no doubt that these studies are helpful to predict the health condition of the LIBs, but unfortunately, most of them are theoretical studies. They have not been verified experimentally. Therefore, there is still a gap between the theoretical research results and the real engineering application. In this study, to predict the capacity fade of the two types of battery systems, the total charging and discharging energy data of the EV were recorded during the test under the NEDC. Then, the capacity degradation state of the battery system was estimated by comparing the recorded data with the battery capacity fade curves provided by the manufacturer. As shown in Fig. 5, the capacity fade curve of the two types of batteries can be obtained when the battery capacity reaches 80% of its original capacity.

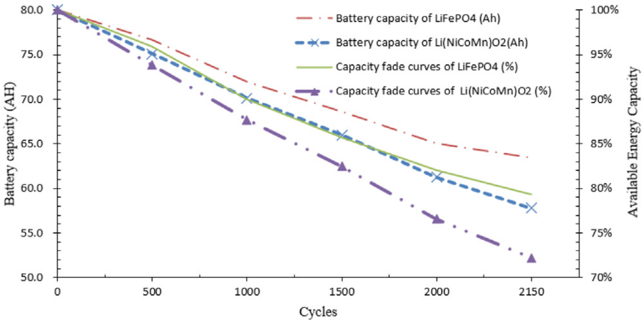


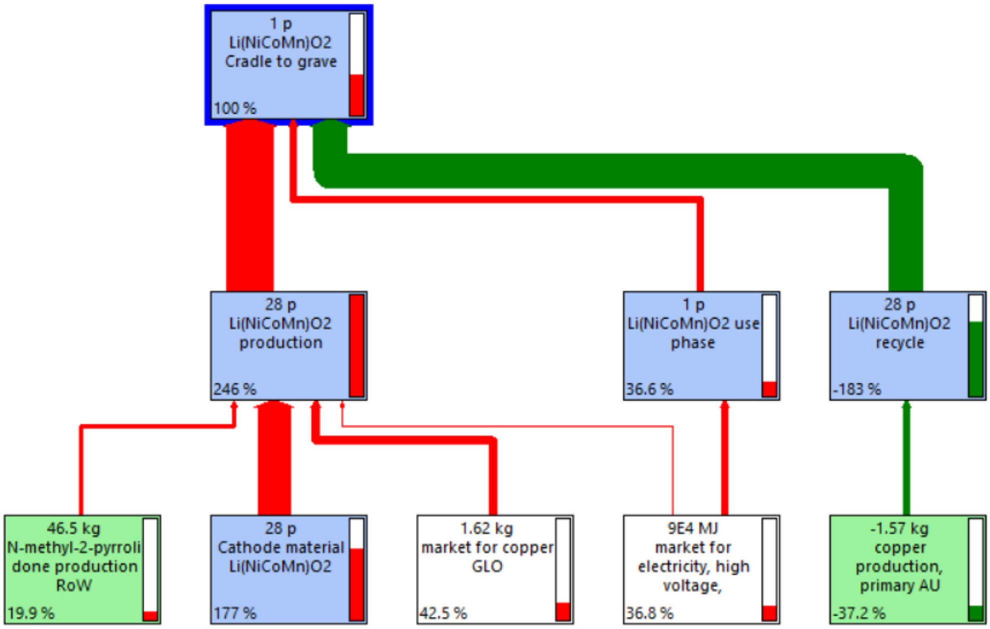
Fig. 5. The capacity fade curves of $Li(NiCoMn)O_2$ and $LiFePO_4$ batteries.

From Fig. 5, it is found that when the battery capacity reaches 80% of its original capacity, the number of cycles obtained when the car is equipped with a $LiFePO_4$ battery is about 1.26 times of that obtained when the car is equipped with a $Li(NiCoMn)O_2$ battery, i.e. 2101 charge and discharge cycles when equipped with a $LiFePO_4$ battery, and 1673 cycles when equipped with a $Li(NiCoMn)O_2$ battery. Based on the LIBs system parameters and the test results, the energy consumption and the number of batteries needed, when using the two types of battery systems, the average C-rate is about 0.2C and the corresponding mileage is 200,000 km, are listed in Table 4.

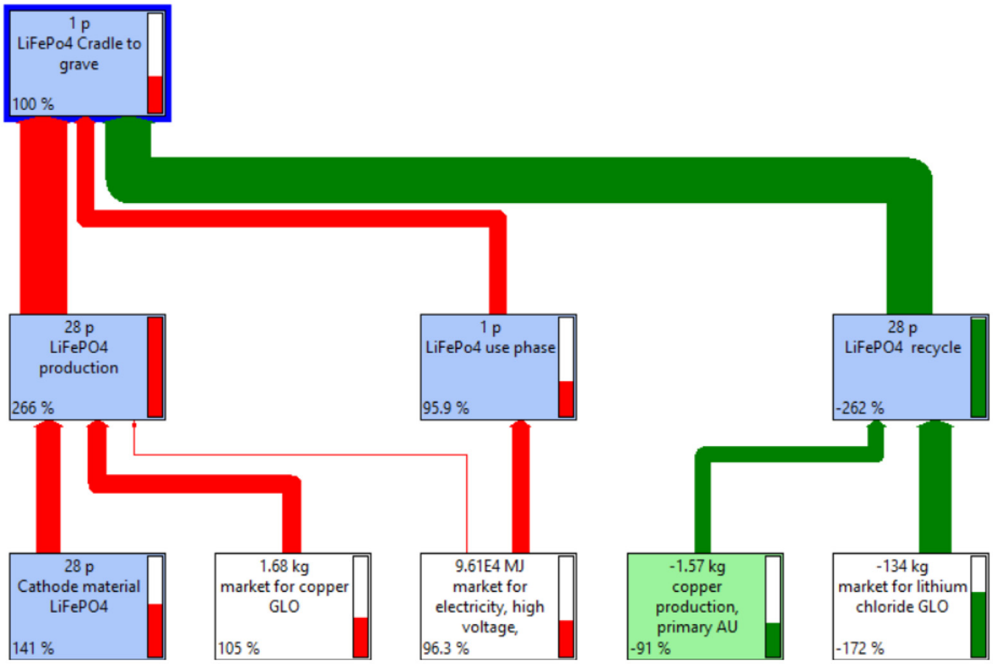
2.5. The phase of recycling

At present, three methods, namely echelon utilization, pyrometallurgy and hydrometallurgy, are popularly used to recycle EV LIBs. Echelon utilization is the simplest method of reusing batteries that have been decommissioned from the purposed applications. Usually, when the capacity of a battery decays to 80% of its original capacity, the battery will be decommissioned (Huijbregts et al., 2017). However, this does not necessarily mean the end of its life. It will be used for other applications that have lower capacity requirements, such as distributed energy storage, backup power supply, home energy storage, sightseeing cars, etc. It should be noted that after the battery system is recycled using the echelon utilization method, the battery cells in it will be reorganized to form a new battery system, starting a new life cycle in their subsequent application.

Since different types of EV batteries are made of different materials, the recycling methods to be used and recycled products will be different. $Li(NiCoMn)O_2$ batteries are usually recycled using the hydrometallurgy method, or recycled using hydrometallurgy and pyrotechnical methods in combination. In these methods, chemical solvents are used to dissolve the various metal materials (e.g. nickel, cobalt, and manganese) in $Li(NiCoMn)O_2$ batteries, and then these metal elements can be separated in the leachate. Since the cathode of $LiFePO_4$ battery does not contain precious metals (e.g. nickel, cobalt, manganese, etc.), the process for recycling this type of battery and the recycled products will be different from those in the circumstance of recycling $Li(NiCoMn)O_2$ batteries. For example, when recycling $LiFePO_4$ batteries using hydrometallurgy method, firstly, the $LiFePO_4$ batteries will be discharged, disassembled, and crushed to obtain lithium iron phosphate powder. Then, the lithium iron phosphate powder will be heated, pulped, acid leached, transformed, and alkalized to remove impurities. Finally, the purified lithium chloride solution is filtered as a recycled product to realize the recovery of lithium in the decommissioned $LiFePO_4$ batteries.



(a) LCA network model for Li(NiCoMn)O$_2$ batteries(GLO=global, RoW= Rest-of-World, AU= Australia)



(b) LCA network model for LiFePO$_4$batteries

Fig. 6. LCA network models for assessing the abiotic depletion impact of the two types of batteries.

In view of the hydrometallurgical method is widely used in China for recycling decommissioned LIBs, it will be applied to recycle the two types of EV batteries of interest in this study to investigate the different environmental impacts of the two types of batteries in the phase of recycling. The data for performing the environmental impact assessment of LIBs in the recycling phase come from a Chinese waste battery recycling company, and the inventory data associated with the recycling of 1 kWh of decommissioned Li(NiCoMn)O$_2$ batteries and LiFePO$_4$ batteries are listed in Appendix Tables A.7 and A.8.

3. Life cycle environmental impact assessment

Based on the methodology depicted above, the life cycle environmental impact of LiFePO$_4$ and Li(NiCoMn)O$_2$ batteries for electric passenger cars is investigated in this Section. Herein, software SimaPro 9.0 will be used to establish the LCA network models, and the European CML-IA baseline V3.05 method and Global Recipe 2016 Endpoint method will be used to assess the impact of the two types of battery systems on the environment (European reference Life-Cycle Database , EL.C.D. 3.0).

To assess the life cycle environmental impact of Li(NiCoMn)O$_2$ batteries and LiFePO$_4$ batteries, the corresponding LCA network

Table 5
LCA results of 28 kWh Li(NiCoMn)O_2 battery and $LiFePO_4$ battery (CML-IA baseline V3.05).

No	Impact category	Type of battery	Total	Production phase	Use phase	Recycle phase	Transport phase
1	Abiotic depletion (Kg Sb eq)	Li(NiCoMn)O_2	7.1E−03	1.8E−02	2.6E−03	−1.4E−02	0.0E+00
		$LiFePO_4$	2.9E−03	7.7E−03	2.8E−03	−7.6E−03	0.0E+00
2	Abiotic depletion (fossil fuels) (MJ)	Li(NiCoMn)O_2	2.8E+05	3.4E+04	2.5E+05	−1.0E+04	7.6E+02
		$LiFePO_4$	2.9E+05	2.1E+04	2.7E+05	−1.1E+03	8.4E+02
3	Global warming (GWP 100a) (Kg CO_2 eq)	Li(NiCoMn)O_2	3.1E+04	2.6E+03	2.9E+04	−9.6E+02	5.4E+01
		$LiFePO_4$	3.2E+04	1.3E+03	3.1E+04	−3.0E+02	5.9E+01
4	Ozone layer depletion (ODP) (Kg CFC-11 eq)	Li(NiCoMn)O_2	3.1E−04	2.3E−04	1.2E−04	−3.8E−05	2.2E−09
		$LiFePO_4$	2.0E−04	1.4E−04	1.3E−04	−6.1E−05	2.4E−09
5	Human toxicity (Kg 1,4-DB eq)	Li(NiCoMn)O_2	1.1E+04	1.0E+03	9.4E+03	2.0E+02	4.7E+01
		$LiFePO_4$	1.1E+04	1.2E+03	1.0E+04	−7.0E+02	5.1E+01
6	Fresh water aquatic ecotoxicity (Kg 1,4-DB eq)	$LiFePO_4$	1.2E+04	2.2E+03	6.8E+03	2.8E+03	1.7E+01
		$LiFePO_4$	7.4E+03	4.5E+02	7.3E+03	−3.3E+02	1.8E+01
7	Marine aquatic ecotoxicity (Kg 1,4-DB eq)	Li(NiCoMn)O_2	5.1E+07	3.5E+06	4.6E+07	2.1E+06	6.3E+04
		$LiFePO_4$	4.9E+07	1.5E+06	4.9E+07	−9.9E+05	7.0E+04
8	Terrestrial ecotoxicity (Kg 1,4-DB eq)	Li(NiCoMn)O_2	3.0E+01	7.6E+00	2.8E+01	−5.4E+00	2.2E−03
		$LiFePO_4$	3.0E+01	1.7E+00	3.0E+01	−1.6E+00	2.4E−03
9	Photochemical oxidation (Kg C_2H_4 eq)	Li(NiCoMn)O_2	5.0E+00	3.0E+00	4.8E+00	−2.8E+00	1.0E−02
		$LiFePO_4$	4.9E+00	2.9E−01	5.1E+00	−1.5E−01	1.2E−01
10	Acidification (Kg SO_2 eq)	Li(NiCoMn)O_2	1.4E+02	7.4E+01	1.3E+02	−6.9E+01	5.1E−01
		$LiFePO_4$	1.4E+02	6.2E+00	1.4E+02	−5.3E+00	5.6E−01
11	Eutrophication (Kg PO_4 -eq)	Li(NiCoMn)O_2	3.2E+01	4.4E+00	2.8E+01	−1.1E+00	1.1E−01
		$LiFePO_4$	3.0E+01	1.9E+00	3.1E+01	−2.3E+00	1.2E−01

Note: CO2 eq = Carbon dioxide equivalent; Sb eq = Antimony equivalent; CFC-11 eq = Trichlorofluoromethane equivalent; C_2H_4 eq = Ethylene equivalent; SO_2 eq = Sulfur dioxide equivalent; PO_4 —eq = Phosphate equivalent; 1,4-DB eq = 1,4-dichlorobenzene-equivalents.

models are developed in software SimaPro 9.0. To facilitate understanding of the LCA network models, the models developed for assessing the abiotic depletion impact of Li(NiCoMn)O_2 batteries and $LiFePO_4$ batteries are shown in Fig. 6 as illustrative examples.

From Fig. 6, it is seen that the LCA network model is an intuitive description of the pollution sources and their contribution to pollution. The two LCA network models shown in Fig. 6(a) and (b) are more or less different due to the differences of the two types of batteries in materials, production method, and recycling process. In the models, red lines represent increasing pollution, while the green lines represent offsetting pollution. The thickness of the lines, which corresponds to the percentage value at the bottom and the ruler on the right side of each block, is used to indicate the contribution of each pollution source to the pollution. In other words, the thicker the lines, the more pollution will be generated or offset by the pollution sources. Therefore, the major pollution sources in each evaluation index can be readily identified from the LCA network models developed. With the aid of the LCA network models developed in software SimaPro 9.0, the life cycle environmental impact of Li(NiCoMn)O_2 batteries and $LiFePO_4$ batteries is studied in this paper by assessing the potential pollution of the two types of batteries in 11 aspects. They are (1) Abiotic depletion, (2) Abiotic depletion (fossil fuels), (3) Global warming (GWP 100a), (4) Ozone layer depletion, (5) Human toxicity, (6) Fresh water aquatic ecotoxicity, (7) Marine aquatic ecotoxicity, (8) Terrestrial ecotoxicity, (9) Photochemical oxidation, (10) Acidification, and (11) Eutrophication. The corresponding assessment results for the two types of batteries are listed in Table 5. In the table, the values listed in the column of 'Total' is the linear sum of the values given in the columns of 'Production Phase', 'Use Phase', 'Recycle Phase', and 'Transport Phase'.

From Table 5, it is found that

- When evaluating from different perspectives, the batteries will show different impacts on the environment. From the assessment results of the 11 evaluation indices, it is found that the batteries will generate environmental pollution mainly in five aspects. They are (2) Abiotic depletion (fossil fuels), (3) Global warming (GWP 100a), (5) Human toxicity, (6) Fresh water aquatic ecotoxicity, and (7) Marine aquatic ecotoxicity;
- The batteries have different environmental impacts in different phases of their life. Among the four phases listed in the table, the battery has the most serious pollution to the environment in the 'Use Phase', followed by the 'Production Phase', and then the 'Transport Phase'. Generally, 'Recycle Phase' is usually considered a phase to offset environmental pollution. However, the interesting thing is that the results listed in Table 5 indicate that this is not always true. For example, it is found from Table 5 that more 'Human toxicity', 'Fresh water aquatic ecotoxicity', and 'Marine aquatic ecotoxicity', are caused, rather than offset, during the recycling process of Li(NiCoMn)O_2 batteries;
- Different types of batteries have different environmental impacts. For example, due to the use of some metal materials (e.g. nickel, chromium, manganese, etc.) that can produce a lot of pollutants, Li(NiCoMn)O_2 batteries is overall not so environmentally friendly as $LiFePO_4$ batteries in the 'Production Phase', although Li(NiCoMn)O_2 batteries produce less 'Human toxicity' than $LiFePO_4$ batteries do in this phase. By contrast, Li(NiCoMn)O_2 batteries are more environmentally friendly than $LiFePO_4$ batteries in all 11 aspects in both 'Use Phase' and 'Transport Phase'. This is mainly because Li(NiCoMn)O_2 batteries have higher energy density and lighter weight than $LiFePO_4$ batteries. It is well known that moving heavier objects will always consume more energy, thereby causing more pollution to the environment;
- The values listed in column 'Total' indicate that in comparison with $LiFePO_4$ batteries, Li(NiCoMn)O_2 batteries produce less pollution in their whole life in terms of 'Abiotic depletion (fossil fuels)' and 'Global warming', while producing more pollution in their whole life in terms of 'Abiotic depletion', 'Ozone layer depletion', 'Fresh water aquatic ecotoxicity', 'Marine aquatic ecotoxicity', 'Photochemical oxidation', and 'Eutrophication'. Both types of batteries cause almost the same amount of pollution in terms of 'Human toxicity', 'Terrestrial ecotoxicity', and 'Acidification'.

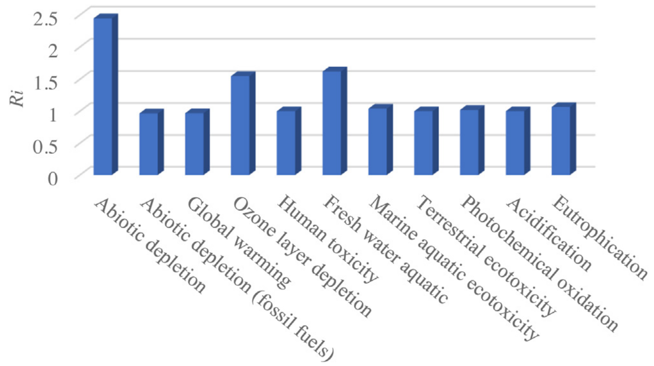


Fig. 7. Calculation results of $R_i(i = 1, 2, \ldots, 11)$.

Herein, a question arises, i.e. which type of batteries, on earth, is more environmentally friendly? Apparently, it is difficult to get an answer to this question directly from Table 5. In order to answer this question, use x_i and $y_i(i = 1, 2, \ldots, 11)$ to represent the 'Total' values of the 11 category indices of Li(NiCoMn)O_2 batteries and $LiFePO_4$ batteries, respectively. Then, a ratio of

$$R_i = x_i/y_i \qquad (i = 1, 2, \ldots, 11) \tag{1}$$

will indicate which type of battery will cause more pollution in category i. In other words, $R_i > 1$ indicates that Li(NiCoMn)O_2 batteries cause more pollution than $LiFePO_4$ batteries do in category i; $R_i = 1$ indicates that both types of batteries cause the same amount of pollution in category i; and $R_i < 1$ indicates that Li(NiCoMn)O_2 batteries cause less pollution than $LiFePO_4$ batteries do in category i. Hence, the values of R_i for all 11 category indices are calculated, and the calculation results are shown in Fig. 7.

From Fig. 7, it is seen that the values of R_i for categories (1) Abiotic depletion, (4) Ozone layer depletion, and (6) Fresh water aquatic ecotoxicity are larger than 1, and the values of R_i for the other eight categories are not larger than 1. Therefore, the average value of $R_i(i = 1, 2, \ldots, 11)$ is calculated as a general assessment criterion to judge which type of batteries is generally more environmentally friendly, i.e.

$$R = \frac{1}{n}\sum_{i}^{n} R_i \qquad (i = 1, 2, \ldots, n \text{ and } n = 11) \tag{2}$$

When $R > 1$, it implies that $LiFePO_4$ batteries are more environmentally friendly than Li(NiCoMn)O_2 batteries; when $R < 1$, it implies that Li(NiCoMn)O_2 batteries are more environmentally friendly than $LiFePO_4$ batteries; and when $R = 1$, it implies that the two types of batteries have an equal impact to the environment.

Then, the value of general assessment criterion R is calculated using Eq. (1) and the data shown in Fig. 8. It is obtained that $R =$ 1.24, which means that in the whole life cycle, $LiFePO_4$ batteries are generally more environmentally friendly than Li(NiCoMn)O_2 batteries.

In order to further confirm the assessment result obtained using the aforementioned European CML-IA baseline V3.05 method, an alternative tool, Global ReCiPe2016 (Huijbregts et al., 2017), is also adopted in this study for assessing which type of battery is more environmentally friendly throughout their life cycle. Global ReCiPe2016 provides a state-of-the-art method to convert life cycle inventories to a limited number of life cycle impact scores on midpoint and endpoint level (Huijbregts et al., 2017). In this method, the life cycle impact of the batteries in three areas (i.e., human health, ecosystem quality, and resource scarcity) are assessed. The overview of Global ReCiPe2016 method is shown in Fig. 8 (Huijbregts et al., 2017).

From Fig. 8, it is seen that in contrast to the European CML-IA baseline V3.05 method, the environmental impact of the batteries in more impact categories (i.e., 16 categories) are evaluated by Global ReCiPe2016 method. The final calculation results of 'Damage Assessment' and 'Single Score' obtained using such a method are listed in Table 6.

From Table 6, it is seen that all 'Damage Assessment' and 'Single Score' values of $LiFePO_4$ batteries in the three areas are smaller than those of Li(NiCoMn)O_2 batteries. Consequently, the total 'Single Score' of $LiFePO_4$ batteries is only 4.9, which is obviously smaller than the total 'Single Score' of Li(NiCoMn)O_2 batteries. Thus, it can be concluded that for the electric passenger car, $LiFePO_4$ batteries are more environmentally friendly than Li(NiCoMn)O_2 batteries when evaluated from the perspective of the entire life cycle.

Obviously, both the European CML-IA baseline V3.05 method and Global ReCiPe2016 method have suggested that $LiFePO_4$ batteries are generally more environmentally friendly than Li(NiCoMn)O_2 batteries when used in pure electric passenger cars. However, some key features of the two types of batteries have been identified in the study. They should be particularly noted because these features may provide suggestions for future research and optimal applications of EV batteries. These features include:

Raw materials — The precious metals used in Li(NiCoMn)O_2 batteries (such as nickel, cobalt, manganese, etc.) are toxic and therefore harmful to the environment. However, Li(NiCoMn)O_2 batteries achieve higher energy density after using these harmful metal materials. By contrast, the iron metal compounds used in $LiFePO_4$ batteries are more environmentally friendly, but the energy density of LiFePO4 batteries is relatively lower than that of Li(NiCoMn)O_2 batteries. Hence, how to use environmentally friendly materials to achieve high energy density batteries will be one of the important issues that need to be solved in the future.

Optimal applications — Because $LiFePO_4$ batteries have a lower energy density, they are heavier than Li(NiCoMn)O_2 batteries of the same capacity. This means that those electric passenger cars that are equipped with $LiFePO_4$ batteries are heavier, thereby consuming more energy and generating more pollution during transportation, than those equipped with Li(NiCoMn)O_2 batteries. This is indeed a negative issue of $LiFePO_4$ batteries when applied to the EVs. However, this will no longer be a problem when $LiFePO_4$ batteries are applied to an area where the battery does not need to be moved frequently. This means that in comparison with the application to the EVs, $LiFePO_4$ batteries probably can gain more benefit when used for energy storage.

Recycling — Recycling can usually offset battery pollution to the environment, but it is not always true. For example, for the scenarios considered in this paper, it is true for $LiFePO_4$ batteries, but it is not always true for Li(NiCoMn)O_2 batteries because more 'Human toxicity', 'Fresh water aquatic ecotoxicity', and 'Marine aquatic ecotoxicity', are resulted, rather than offset, during the recycling process of Li(NiCoMn)O_2 batteries. Therefore, how to improve the recycling method to reduce or completely avoid the generation of pollutants in the recycling process of the batteries will be an important topic that needs to be studied in the future.

4. Conclusions

To understand the impact of different types of LIBs on the environment when used in the EVs, the life cycle environmental impact of $LiFePO_4$ batteries and Li(NiCoMn)O_2 batteries that are used in pure electric passenger cars is investigated in this paper. The research results have shown that

Table 6
LCA results of 28 kWh batteries using the Global ReCiPe2016 method.

Damage category	Damage assessment		Single score (kPt)	
	$LiFePO_4$	$Li(NiCoMn)O_2$	$LiFePO_4$	$Li(NiCoMn)O_2$
Human health	0.994 (DALY)	1.06 (DALY)	4.45	4.73
Ecosystems	0.000978 (species.yr)	0.001(species.yr)	0.464	0.478
Resources	699 (USD2013)	722 (USD2013)	0.0049	0.005
Total	N/A	N/A	4.9	5.2

Note: DALY = disability adjusted life years, species.yr= species.year, USD2013 = united states dollar. 2013.

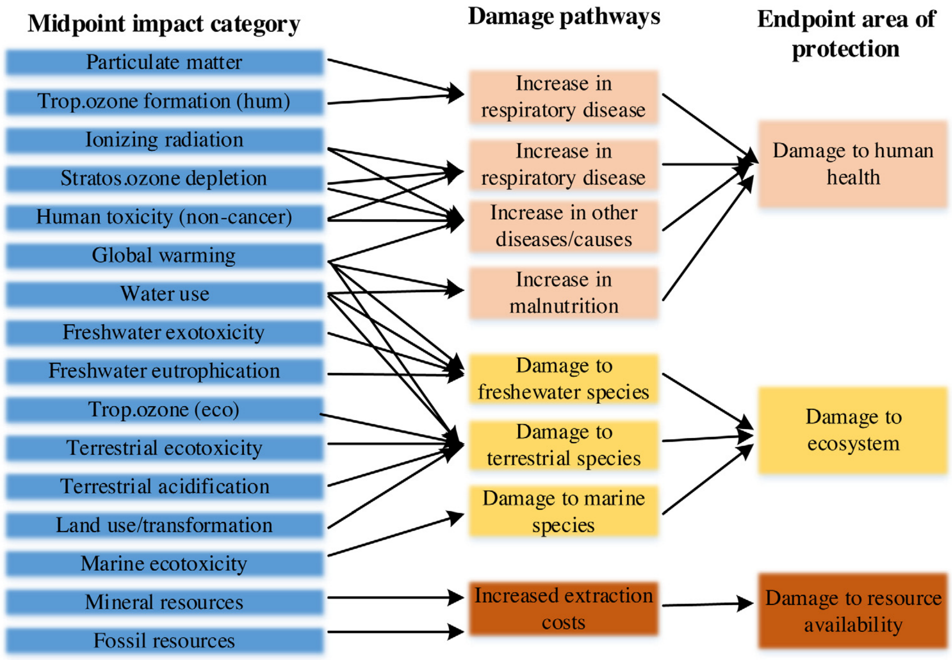


Fig. 8. Overview of Global ReCiPe2016 method.

(1) From the perspective of the entire life cycle, $LiFePO_4$ batteries are more environmentally friendly than $Li(NiCoMn)O_2$ batteries when used in pure electric passenger cars, although the electric passenger cars that are equipped with $LiFePO_4$ batteries need to consume more energy during the process of transportation;
(2) For $Li(NiCoMn)O_2$ battery system, the production phase of it is the biggest contributor of abiotic depletion (fossil fuels), followed by its use phase. In terms of the generation of human toxicity and fresh water aquatic ecotoxicity, the production phase and use phase of $Li(NiCoMn)O_2$ battery have almost the same contribution, i.e. the difference of the contributions of the two phases is up to 10%;
(3) For $LiFePO_4$ battery system, most abiotic depletion and ozone layer depletion is produced in its production phase, while almost all abiotic depletion (fossil fuels), global warming (GWP 100a), human toxicity are produced in its use phase.

CRediT authorship contribution statement

Xiong Shu: Conceptualization, Methodology, Software, Writing - original draft, Funding acquisition. **Yingfu Guo:** Formal analysis, Visualization. **Wenxian Yang:** Supervision, Writing - review & editing. **Kexiang Wei:** Supervision, Funding acquisition. **Guanghui Zhu:** Validation, Funding acquisition.

Declaration of competing interest

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Appendix

See Tables A.1–A.8.

Table A.1

Materials and energy flows for per kWh cathode material production of $LiFePO_4$.

	Items	Unit	Quantity
Input	Electricity	kWh	4. 91E+00
	Iron phosphate	Kg	1. 91E+00
	Lithium carbonate	Kg	8.02E−01
	Glucose	Kg	2.31E−01
	Carbon black	Kg	0.81E+00
	Styrene acrylate latex	Kg	2.1E−03
	Nitrogen	Kg	2.12E−02
	Water	Kg	5.87E+00
Output air pollution	Lithium carbonate	g	4.10E+00
	Dust	g	2.12E−01
Output water pollutants	Suspended solids, unspecified	g	1.52E−02
	Phosphorus compounds, unspecified	g	1.21E−03
Production	Cathode material production	Kg	2.11E+00

Table A.2

Materials and energy flows for per kWh anode material production of $LiFePO_4$.

	Items	Unit	Quantity
Input	Electricity	kWh	7.36E+00
	Graphite	kg	1.45E+00
	PVDF	kg	1.15E−02
	Methyl-2-pyrrolidone	kg	2.31E−02
	water	kg	7.68E+00
	Asphalt	kg	1 .11E−01
Output air pollution	Dust	g	4.39E−01
	Non-methane volatile organic compounds	g	7.46E−01
	Soot	g	1.76E−01
Production	Anode material production	Kg	1.264+00

Table A.3

Materials and energy flows for per kWh electrolyte production of $LiFePO_4$.

	Items	Unit	Quantity
Input	Electricity	kWh	3.36E+00
	Steam	kg	1 .15E+01
	Water	kg	8.24E+01
	Ethylene glycol dimethyl ether	kg	6.23E−01
	Lithium chloride	kg	2.23E−01
	Lithium hexafluorophosphate (LiPF6)	kg	0.53E−02
	Ethylene carbonate (EC)	kg	1.12E−02
	Dimethyl carbonate (DMC)	kg	1.08E−02
	Nitrogen	kg	4.89E−01
	Sodium hydroxide	kg	7.08E−02
Output air pollution	Carbon dioxide	g	8.45E+02
	Fluoride	g	8.82E−02
	Volatile organic compounds	g	3.40E−01
	Dust	g	4.96E−02
	Hydrogen chloride	g	1.94E−01
Output water pollutants	COD, Chemical oxygen demand	g	1.30E−01
	Ammonia, as N	g	1.27E−02
	Fluoride	g	4.32E−03
	Suspended solids, unspecified	g	1.25E−01
Production	Electrolyte production	Kg	1.180E00

Table A.4

Materials and energy flows for per kWh cathode material production of $Li(NiCoMn)O_2$.

	Items	Unit	Quantity
Input	Precursor	Kg	1.732E+00
	Lithium carbonate	Kg	0.468E+00
	Oxygen	m^3	4.70E+00
	Aluminum oxide	Kg	0.608E−02
	Water	Kg	2.484E+00
Output air pollution	Carbon dioxide	Kg	0.420E+00
	Dust	g	1.276E−01
	Nickel	g	1.012E−01
	Cobalt	g	0.404E−01
	Manganese	g	0.608E−01
Output water pollutants	Chemical oxygen demand	g	2.964E−01
	Biological oxygen demand	g	0.772E−01
	Suspended solids, unspecified	g	2.336E−01
	Ammonia nitrogen	g	0.464E−01
Production	Cathode material production	Kg	1.77+00

Table A.5
Materials and energy flows for per kWh anode material production of $\mathrm{Li(NiCoMn)O_2}$.

	Items	Unit	Quantity
Input	Electricity	kWh	2.21E+00
	Graphite	kg	1.96+00
	Water	Kg	1.74E+00
	Asphalt	Kg	1.05+00
Output air pollution	Dust	g	4.39E−01
	Non-methane hydrocarbons	g	7.46E−01
	Soot	g	1.76E−01
Production	Anode material production	Kg	1.023E+00

Table A.6
Materials and energy flows for per kWh electrolyte production of $\mathrm{Li(NiCoMn)O_2}$.

	Items	Unit	Quantity
Input	Electricity	kWh	3.01E+00
	Steam	kg	1 .15E+01
	Water	kg	3.60E−00
	Ethylene carbonate	kg	1.31E+00
	Dimethyl carbonate	kg	0.45+00
	Lithium hexafluorophosphate	g	1.51E−02
	Nitrogen	kg	4.62E−01
	Sodium hydroxide	kg	7.31E−02
Output air pollution	Carbon dioxide	g	9.20E+02
	Fluoride compounds	g	9.61E−03
	volatile organic compounds	g	3.70E−01
	Dust	g	5.40E−02
	Hydrogen fluoride	g	8.08E−02
	Hydrogen chloride	g	2.11E−01
Output water pollutants	Chemical oxygen demand	g	1.42E−01
	Ammonia nitrogen	g	1.38E−02
	Fluoride compounds	g	4.70E−03
	Suspended substances	g	1.36E−01
Production	Electrolyte production	Kg	1.67E+00

Table A.7
Inventory data for the recycling of 1 kWh $\mathrm{Li(NiCoMn)O_2}$ battery with hydrometallurgy method.

	Items	Unit	Quantity
Input	Electricity	kWh	18.01E+00
	Hydrogen chloride	kg	1.75E−01
	Water	kg	10.31E+01
	Sulfuric acid (30%)	kg	8.27E+00
	Extracting reagent P507	kg	1.45E−02
	Kerosene	kg	2.37E−02
	Sodium hydroxide	kg	16.84E+00
	Hydrogen peroxide	kg	3.17E+00
Output air pollution	Dust	g	2.38E−00
	Carbon dioxide	g	4.38E+00
	Sulfuric acid	g	3.75E−01
	Hydrogen sulfide	g	2.29E+00
	Ammonia	g	6.59E−02
Output water pollutants	Chemical oxygen demand	g	1.03E+01
	Suspended solids	g	1.24E+01
	Biological Oxygen Demand	g	3.64E+00
	Nickel	g	4.75E−02
	Cobalt	g	4.38E−02
	Manganese	g	4.75E−02
	Lithium	g	3.98E+00
	Ammonia nitrogen	g	5.06E−01
Production	Precursor	Kg	1.72E+00
	Copper	Kg	0.76E+00
	Aluminum	Kg	1.01E+00
	Steel	Kg	0.12E+00

Table A.8
Inventory data for the recycling of 1 kWh $LiFePO_4$ Battery with hydrometallurgy method.

	Items	Unit	Quantity
Input	Electricity	kWh	3.01E+00
	Nature gas	kg	1.24E+00
	Hydrochloric acid	kg	5.04E+00
	Water	kg	9.61E+01
	Magnesium dihydroxide	kg	5.85E−01
	Sodium hydroxide	kg	4.86E−01
Output air pollution	Dust	g	3 .03E−01
	Sulfuric acid	g	8.11E−02
	Hydrogen chloride	g	5.43E−01
Production	Lithium chloride	Kg	8.90+00
	Copper	Kg	0.63E+00
	Aluminum	Kg	1.25E+00
	Steel	Kg	0.20E+00

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