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A Critical Review on Electric Vehicle Batteries — Based on Life Cycle Assessment Method

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Abstract

Currently, the production of electric vehicles and the lithium batteries that powers them is increasing significantly. Thus, this dissertation combines the literature review approach and the life cycle assessment (LCA) method to investigate the environmental or social impact of lithium batteries for electric vehicles from cradle to grave. According to the literature review, the environmental impacts of lithium batteries include carbon dioxide and harmful electrolyte emissions, water pollution, air pollution, solid waste emissions, gaseous pollutants, volatile organic compounds, nitrogen oxides, heavy metals, organic pollutants, particulate matter and CO_2 emissions. Therefore, lithium batteries for electric vehicles pose a great environmental concern. In addition, the confusion surrounding the definition of lithium batteries in LCA can pose a significant concern. The in-depth analysis reveals that there is a lack of uniform data on EV lithium batteries, a low recycling rate of lithium batteries, and a lack of waste stream management. There is no uniformity in the technology and development of lithium batteries among countries such as China, Canada, and the USA. As a result, the secondary data may only represent this region. Besides, the literature consulted covers a long period of time. There is little possibility that the negative environmental impact of earlier technology like the burning of lithium batteries in incinerators can now be improved. Moreover, lithium batteries are still in the development stage. Therefore, there is still room for potential development in the future.

Keywords: lithium batteries, life cycle assessment, environmental impacts

1. Introduction

1.1 Research Background and Significance

In early 1997, an electric vehicle was referred to as a vehicle that supplies electricity to an electric motor and then to the wheels (Fu, 1997). As electric vehicles gradually spread through society, Kihm (2014) pointed out that electric cars would replace fuel cars in the future. According to the China Automotive Low Carbon Action Plan Report 2021, the total carbon emissions of China's automotive life cycle were estimated to be around 670 million tonnes of CO_2 in 2020, with fuel cars accounting for 74%. This is because conventional fuel cars require coal power to operate. However, the environmental impact of electric vehicles can be significantly reduced by using renewable energy sources such as solar and bio-energy to power them (China Automobile Center, 2021). Thus, electric vehicles have many advantages over fuel-powered vehicles that are entirely reliant on petrol. In response to climate change, the Paris Agreement recently specifies that efforts must be taken to keep the increase in the world's average temperature to 1.5 °C and maintained at 2 °C by the end of the century.

Therefore, the continuous use of fuel-powered vehicles would have a serious impact on the environment. In addition, the use of fuel-powered vehicles has been banned in some nations. For example, the US will completely ban fuel vehicles in 2029 while nations like China, Tokyo, and the UK will completely ban fuel vehicles in 2030 (Tencent.com, 2021). New research by Canalys also predicts that global electric vehicle (EV) sales would grow by 39% annually, reaching 30,000 units in 2020. By 2028, EVs are expected to account for nearly half of global passenger car sales (Canalys, 2020). These factors make the promotion of electric vehicles a worldwide trend.

Current electric vehicles are all powered by lithium batteries. Both Tesla and BYD EV companies use lithium-ion batteries. However, the two companies use different types of batteries. While Tesla uses Lithium Nickel Cobalt Aluminum Oxide (NCA) batteries, BYD uses Lithium Iron Phosphate (LFP) batteries (Klyshko & Mikhailova, 2019). Although Tesla and BYD use distinct approaches to design and produce electric vehicle batteries, they have both achieved products with comparable performance. For example, both companies adopt fast charging technology and good discharge power (Klyshko & Mikhailova, 2019). Lithium batteries were chosen as the power source for electric vehicles due to their many advantages.

Compared to traditional batteries like lead acid batteries and zinc carbon batteries, LIBs offer higher efficiency, longer life cycles, high energy density, and stable performance at high temperatures. These characteristics make this technology the most suitable for electric vehicle applications (How, 2019). Nevertheless, the performance of lithium-ion batteries varies depending on the materials used such as cobalt, manganese, iron, nickel, aluminium, and titanate (Zubi, 2018; Hannan, 2018; Zhang, 2018). Therefore, the type of lithium batteries used by every manufacturer of electric vehicles may vary.

Lithium batteries (LIBs) are the most important element in electric vehicles and pose a serious global environmental impact. According to a California study by Kang et al. (2013), lithium batteries are classified as hazardous waste in the US owing to the presence of excessive levels of cobalt and copper as well as hazardous metals, which are potential sources of environmental pollutants. Lithium batteries contain a high amount of metallic elements, which can pollute the environment if they are not properly disposed of. For example, the direct disposal of lithium batteries in landfills may lead to leakage of chemical elements. According to Zhao (2016), lithium batteries also have a high energy density. For instance, a short circuit in lithium batteries can easily induce thermal runaway, leading to an explosion. Therefore, lithium batteries can affect human health and safety. In summary, this study investigates the concerns posed by lithium batteries in electric vehicles.

1.2 Main Research Directions

This paper will use a literature review approach to understand the current status of lithium batteries for electric vehicles by reviewing peer-reviewed articles, international journals, NGO reports, etc. Emphasis will be placed on understanding the environmental impact of lithium batteries from raw material to production and disposal. This direction of research can be achieved by utilising the widely used framework, Life Cycle Assessment (LCA). This framework allows for a thorough evaluation of the stages of lithium batteries for electric vehicles in order to elucidate whether the cradle-to-grave emissions and pollution of lithium batteries have an impact on the environment. It will also take into account the existing or unresolved problems within the framework.

2. Methodology

This dissertation uses literature review as its primary methodology. The secondary data of the dissertation will mainly include journals, dissertations, NGO reports, academic papers, government reports. By carefully evaluating many research sources, this dissertation will present the concerns of electric vehicle batteries in a step-by-step manner using the Life Cycle Assessment (LCA) framework. However, this LCA was only analysed using data that had already been summarised by other scientists. Besides, the study will focus on each stage of the process rather than concentrating on one country. The regionally focused analysis will be considered.

In this dissertation, Life Cycle Assessment (LCA) framework will be used to conduct the assessment. As shown in Figure 1, LCA refers to the environmental factors and potential impacts throughout the product lifecycle (i.e., cradle to grave), including the sourcing of raw materials for production, usage, and disposal. The general categories of environmental impacts that must be considered include resource consumption, human health, and ecological consequences (Klopffer, 2014). The life cycle of lithium batteries begins with the mining of resources, which are then processed using a variety of methods to produce lithium batteries. Subsequently, they are installed into electric vehicles and put to use. Lithium batteries have a low life span and can be reasonably discarded or recycled after use. This is the complete life of lithium batteries. However, lithium batteries produce incidents such as air pollution emissions or heavy metal leaks from resource extraction. Therefore, LCA is used to explore the concerns of lithium batteries for electric vehicles. This thesis aims to develop a life cycle assessment of lithium batteries from production to the grave in order to analyse the environmental impacts of current lithium batteries for electric vehicles.

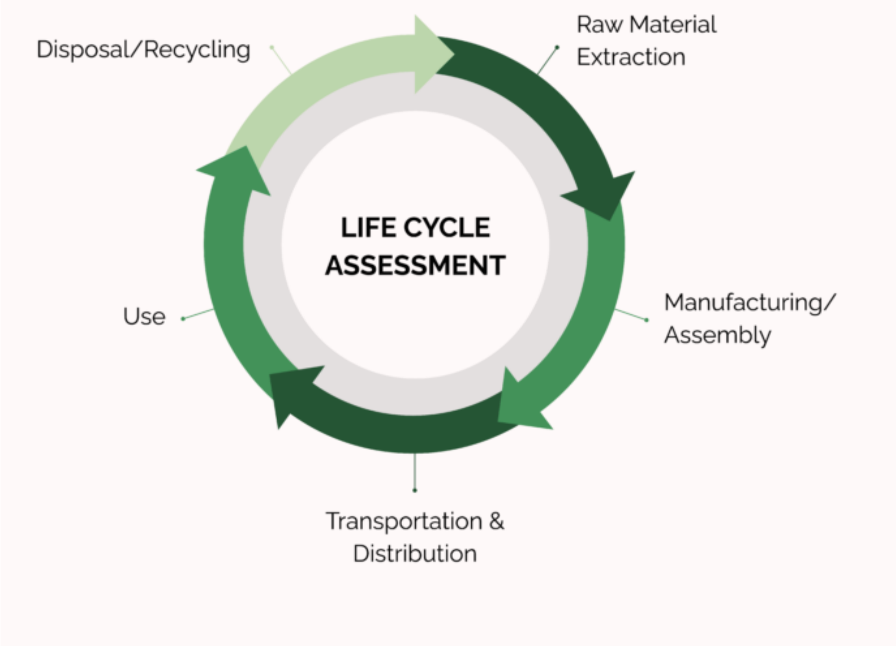

Figure 1. Life cycle assessment (Source: Matthew Eckelman & Sarah Nunberg, n.d.)

3. Environmental Impacts Evaluation Through LCA

The environmental impact of lithium batteries is multifaceted. The adoption of the LCA approach in lithium batteries research involves an analysis of multiple aspects of the production, usage, disposal, and recycling stages of lithium batteries. As shown in Figure 2, the emissions from LIBs in different forms can be determined during the life cycle assessment of LIBs.

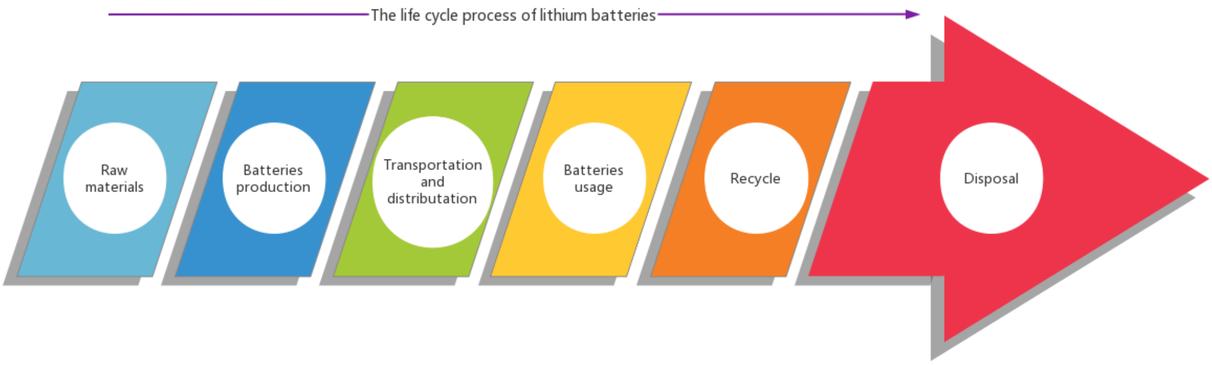

Figure 2. The life cycle assessment of LIBs

3.1 The Environmental Impact from a Raw Materials Perspective

First and foremost, it is important to understand how lithium batteries are manufactured. As shown in Figure 3, LIBs are made from a large number of raw materials, including metal elements. Figure 3 indicates how much of the global total of this element is accounted for by countries. According to Meshram et al. (2020), most of the metallic elements for lithium batteries such as lithium, cobalt, nickel, and manganese are recovered from ores. These metallic elements are commonly used in the manufacture of cathode materials for lithium-ion batteries. Meshram et al. (2020) contend that a few countries own a large share of the raw materials for lithium batteries, as shown in Figure 3. South Africa produces the majority of the world's manganese, accounting for 75 percent of the total global manganese resources. Chile and Argentina produce the majority of the world's lithium, accounting for 53 percent and 14%, respectively of the total global lithium resources (Meshram et al., 2020). Thus, the raw materials for lithium batteries are purchased globally from these nations. However, Song et al. (2019) contend that any nation that produces lithium batteries may face a threat from a sudden collapse of the global supply chain if there is economic or political instability in the country where the raw material is extracted.

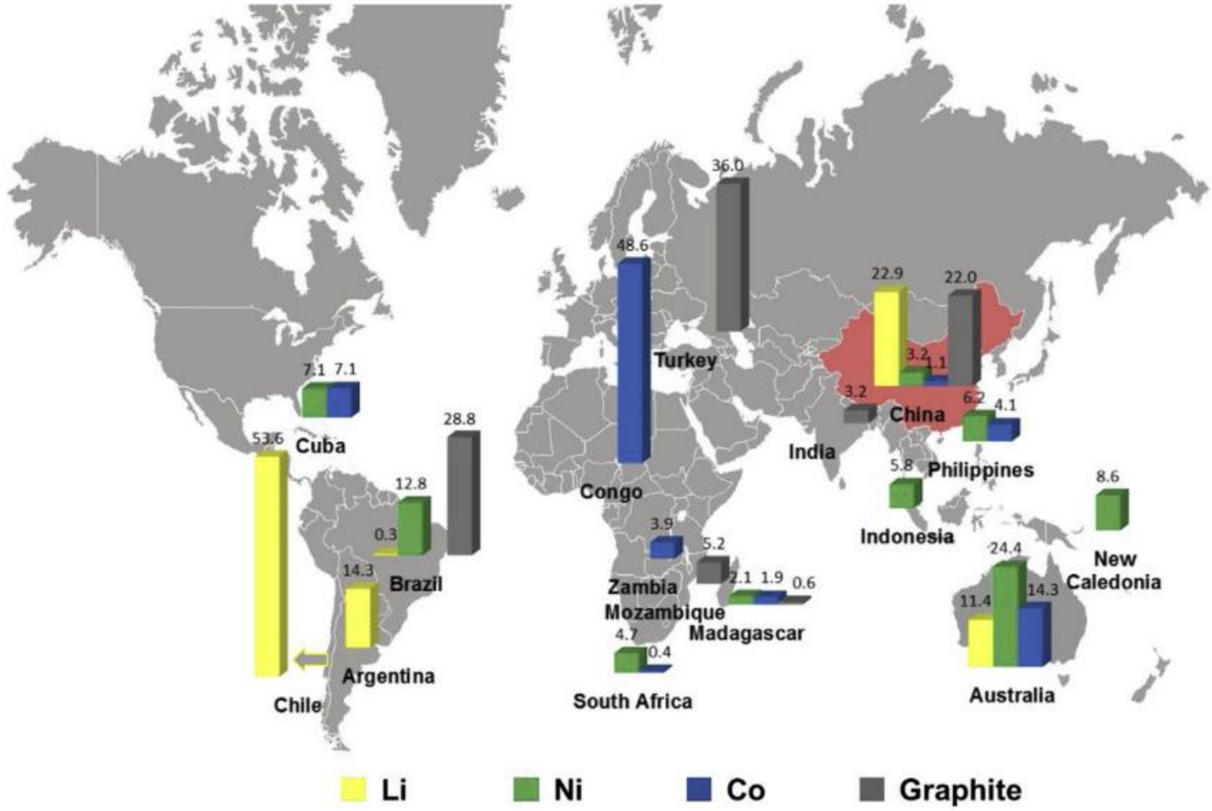

Figure 3. Global distribution of LIBs critical material reserves.

Note: the length of the bar indicates the relative fraction of the total reserves (Source: Song et al., 2019)

Mining, mineral processing, smelting, leaching, and refining are used to transform these raw materials into objects used in batteries. In these processes, wrought aluminium production emits 2~3 kg of CO_2 per kg of lithium batteries, which is more than what a normal alumina refinery would emit. According to Kang et al. (2013), $LiMn_2O_4$ electrode also emits 800-1000 kg of CO_2 per kg of lithium battery production. Furthermore, lithium batteries also consume nearly 500 kg of CO_2, which is sufficient to produce electrolytes such as Dimethyl carbonate (DMC), LiFP6, etc. (Kang et al., 2013). According to Stich et al. (2018), the LiPF6 electrolyte for LIBs produces HF when exposed to water. HF is a toxic substance that can pollute waters and is highly erosive to human bones. It is also harmful to surrounding organisms when leaked into the water. Thus, these electrolytes can be very harmful to the environment after the battery has been depleted. Fortunately, companies that manufacture the raw materials for lithium batteries are now subject to stricter controls and environmental pollution laws in various countries, allowing them to emit or produce less polluting gases.

3.2 The Environmental Impact from a Production Perspective

During the production of lithium batteries, many hazards are generated such as water pollution, air pollution, and pollution from solid waste emissions (Arshad et al., 2022). According to the graphical statistics of Wang (2019), the lithium battery plant in Mainland China was selected as a case study and named Case 1 (Table 1). Case 1 produces 0.22 GWh LIB per year and the electricity consumption of battery production per GWh is 5.24×10^4 KWh. Each GWh of battery production releases 2.95kg of N-Methyl Pyrrolidone (NMP), 29.45 kg of chemical oxygen demand (COD), and 6.95kg of NH3-N into the air and water. 559 kg of domestic waste, 2.45 kg of ordinary industry waste, 114.87 kg of hazardous waste, and 114.87 kg of hazardous waste are released as municipal solid waste.

Table 1. The impacts of battery production per GWh (Source: Wang, 2019)

System	Energy	Environment					
Category	Energy Consumption	Atmospheric Environment	Water Environment		Solid Waste		
Indicator	Electricity	NMP	COD	NH3-N	Domestic	Ordinary industry	Hazardous

					waste	waste	waste
Unit	kWh	kg	kg	kg	kg	kg	kg
Case 1	$5.24*10^4$	2.95	29.45	6.95	559.64	2.45	114.87

These pollutants are harmful to human health and the environment. Additionally, the greenhouse gas emissions from the production of lithium batteries have become a major problem due to the rapid development of electric vehicles and the increasing demand for lithium batteries. For instance, Hao et al. (2017) reported the greenhouse gas emissions of the three most commonly used cathode materials for lithium-ion batteries. They found that 28 kWh of lithium-iron-phosphate (LFP), lithium-nickel-manganese-cobalt (NMC) and $LiMnO_2$ (LMO) cathode materials for the batteries generated approximately 3061 kg CO_2, 2912 kg CO_2 and 2705 kg CO_2 of GHG emissions, respectively. Similarly, McManus (2012) claimed that greenhouse gases are produced during the production of lithium batteries, with an estimated 12.5 kg of CO_2 emitted and 90MJ of energy consumed. The type of cathode chemistry used in the production of lithium batteries also generates considerable greenhouse gas emissions. Despite being widely used and economically suitable, LCOs contribute 80% to GHG emissions. The emitted gas contains 40% carbon monoxide (CO), 20% carbon dioxide (CO_2) and 30% hydrogen (H2) as well as traces of <3% hydrogen fluoride (HF) and ~7% hydrocarbons (Hao et al., 2017). Kim et al. (2016) provided a concise summary of the annual consumption of a particular LG plant in South Korea that produces and manufacture approximately 1 million lithium batteries in 2014. The plant consumes 39% of coal, 22% of natural gas, 30% of nuclear, 5% of oil, 1% of hydroelectric, and 3% of other renewable energy annually. In summary, LIBs generate a range of pollution during the production phase in the life cycle.

3.3 The Environmental Impact from a Transportation and Distribution Perspective

Lithium battery transportation can be broadly classified as shipping and freight transit because the current data does not provide a single count of pollution emissions from the transport of lithium batteries. IEA (2022) claimed international shipping accounts for 2% of global energy-related CO_2 emissions in 2021, signifying that 667 tonnes of CO_2 are emitted into the atmosphere. Freight transport also accounts for 29.4% of global CO_2 emissions, signifying that 2.4 billion tonnes of CO_2 are emitted (Hannan et al., 2018). Data from the European Environment Agency shows that 70% of greenhouse gas emissions originate from road transport (Petrauskiene et al., 2020).

Road traffic pollution contains a wide range of air pollutants such as gaseous pollutants, volatile organic compounds, nitrogen oxides, heavy metals, organic pollutants, and particulate matter. These pollutants can have acute or chronic effects on human organs as well as diverse ecological conditions. Moreover, the carbon dioxide emissions caused by lithium batteries during transportation have an environmental impact. Furthermore, Meshram et al. (2020) elaborate on the need of using fibre, wooden boxes, and other materials to package lithium batteries during transportation in order to avoid electrical short-circuiting. Lithium batteries are susceptible to thermal runaway and other hazards after being short-circuited. Thermal runaway can easily cause spontaneous combustion or even an explosion of the lithium battery, which is detrimental to the safety of the residence. According to the National Transportation Safety Board (NTSB) incident report, a total of 82 accidents involving the transportation of batteries in aircraft have been recorded in the United States; 14 of these accidents relate to lithium batteries while 2 of them led to a serious consequences (NTSB, 2007). According to Downs (2007), a lithium battery recycling plant in Canada experienced a serious fire that started as a result of an internal short circuit in some used lithium batteries that were being stored in a dry and sealed container. Therefore, it is important to follow strict procedures when storing and transporting lithium batteries.

3.4 The Environmental Impact from the Usage Phase Perspective

According to Arshad et al. (2022), the indirect emissions of lithium batteries during usage are influenced by the conversion losses of energy, the carbon intensity of energy, and the amount of energy required to carry the weight of the battery. The indirect emissions originate from a moving vehicle but are emitted from LIBs. Given that the energy efficiency and energy conversion of lithium battery is determined by the operational energy demand of the electric vehicle, it is difficult to determine the precise energy efficiency of lithium battery (Ellingsen, 2017). Battery energy efficiency is the ratio of the energy that can be extracted from the battery to the amount of energy that was previously charged into the battery (Eftekhari, 2017). When studying lithium batteries, it is crucial to assume energy efficiency throughout the use phase (Ellingsen, 2017). Eftekhari (2017) asserts that high energy efficiency must be assumed in order for electrode materials to be of practical interest. On the other hand, Ellingsen (2014) assumed an energy efficiency of 95% and found that the carbon intensity of electricity during charging and vehicle operational requirements can significantly affect the emissions of lithium batteries on LCAs. Thus, Ellingsen (2016) conducted extensive research and found that after covering 180,000 km of driving distance using electric vehicles in Europe, indirect energy emissions caused by conversion losses from vehicles powered by European electricity mix and purely wind-based electricity were 638 kg of CO_2 and 18 kg of CO_2, respectively.

The weight of the lithium battery also affects the amount of indirect energy generated. In order to estimate the indirect energy consumption caused by the weight of the battery, Zackrisson et al. (2010) studied the weight ratio of the vehicle to the lithium battery, the energy demand for vehicle operation, and the effect of the weight of the vehicle on operational energy consumption. In their study, the lithium battery produces an indirect emission of 236 kg of CO_2 when the electric vehicle covered a travel distance of 180,000 km.

The lifespan of lithium batteries in electric vehicles is equally important. In Europe, Marques et al. (2019) used a brand new battery and a battery with 70% of the capacity to measure the driving distance of electric vehicles with different lifetimes for the same energy consumption. As shown in Table 2, the shorter the lifespan of the lithium battery, the more energy is required to travel the same distance. Given that electricity is the only energy source during the use phase of electric vehicles, carbon emissions from the batteries can be mainly related to electricity (Chen, 2022). Therefore, the shorter the lifespan of a lithium battery, the more energy an EV will require to travel the same distance and the more electricity it will require. This will to the emissions of more carbon from the battery. As shown in Table 3, the average life expectancy of an electric battery is 8 years (Song et al., 2019). Moreover, the factors that may affect the life span of lithium batteries include temperature, overcharge, and over-discharge, high current charge and discharge as well as the cycle interval between charging and discharging (Zhang, 2021).

As a result, the need to replace batteries in electric vehicles every eight years will lead to an increase in waste production of LIBs. At the same time, there is an increasing production and consumption of lithium batteries. As shown in Figure 4, LIBs waste consists of chemical elements, including $LiCoO_2$ (LCO), $LiMnO_2$ (LMO), LiNixMnyCo1-x-yO2 (NCM), LiNixCoyAl1-x-yO2 (NCA) (Song et al., 2019). Based on these chemical elements, estimates of waste flux changes have shown that the production of LIBs waste is increasing annually (Song et al., 2019). As the production and disposal of lithium batteries increases, proper disposal and recycling become increasingly important.

Table 2. Driving distances of lithium batteries in electric vehicles with different lifetimes for the same energy consumption (Source: Chen, 2022)

Energy consumption	Driving range (new battery)	Driving range (70% battery)
105 (Wh/km)	229 (km)	160 (km)

Table 3. The lifespan of LIBs, average annual production and consumption of LIBs in China (Source: Song et al., 2019)

Application	Battery electric vehicles
Anticipated LIBs lifespan in the application (years)	8
Typical LIB mass range in different products (kg)	180-400
Production amount in China (2016) (units)	421.8 thousand
Approximate total consumption of LIBs, 2016 (metric tons)	122,330

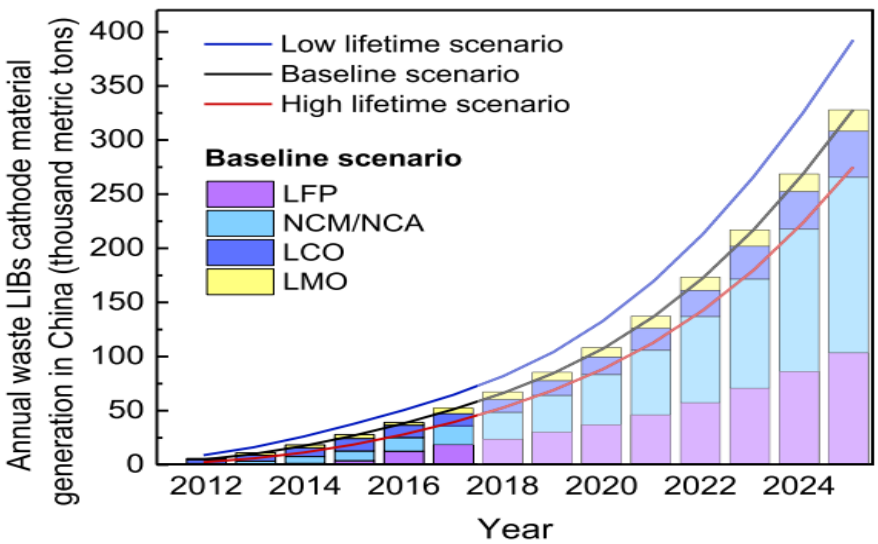

Figure 4. Estimated waste generation from LIBs from 2012 to 2024 (Source: Song et al., 2019)

3.5 The Handling Methods of Spent LIBs

Electric vehicle lithium batteries must be replaced when they reach 80% of their capacity (Tong et al., 2013). Therefore, lithium batteries must be properly disposed of when they reach end-of-life (EOL). The current methods of handling spent lithium batteries are reuse, recycling, and disposal (Hua et al., 2021). Figure 5 depicts the typical waste handling methods as recommended by the European Commission (2008). Wastes hierarchy is a tool for assessing the process of environmental protection, resource, and energy consumption from the most beneficial to the least beneficial actions (Hansen et al., 2002). The waste management hierarchy represents a prioritisation of actions to reduce and manage waste and is often presented graphically in the form of a pyramid (United Nations Environmental Program, 2013). The aim is to extract the maximum practical benefit from the product while generating the least amount of waste, resulting in energy savings and environmental protection. The waste hierarchy is divided into the following categories: avoidance, reuse, recycling, treatment, and disposal. Avoidance means avoiding the production of lithium batteries for electric vehicles. However, avoiding the production of lithium batteries is impossible with the global development of electric vehicles. Reuse is the process of giving spent lithium batteries a second life before they are discarded (European Commission, 2008). Treatment involves recovering energy by incinerating unrecycled lithium batteries waste to energy. However, an explosion or fire may occur when the temperature within the battery rises above a certain threshold. A serious implication may also occur when LIBs are sent to a waste-to-energy facility where the wastes are treated at high temperatures (Winslow et al., 2018). Disposal refers to the act of discarding or landfilling the spent LIBs. Given the aforementioned factors, the handling methods of lithium batteries mainly focus on reuse, recycling, and disposal.

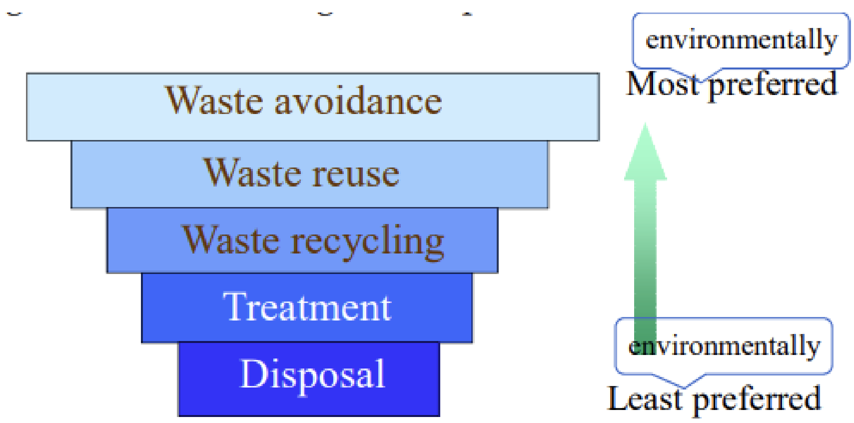

Figure 5. Waste hierarchy (Source: European Commission, 2008)

3.6 Reuse of EV Batteries

Different products can be reused in different ways. Prior to further usage as a product, spent lithium batteries are subjected to repairs, refurbishment, and remanufacturing. According to DeRousseau et al. (2017), remanufacturing and separately repurposing are the two ways of reusing EV batteries. Remanufacturing is the process of repairing or refurbishing electric vehicle battery packs for redeployment. On the other hand. repurposing entails using the EOL LIBs in less-burdened applications for secondary use, such as backup power supplies and power tools (Hua et al., 2021).

By identifying ageing modules and replacing them with qualified components, remanufacturing methods can convert a set of EOL LIBs into fewer qualified packs. Remanufacturing usually includes full battery testing, partial package disassembly, disassembly and replacement, and reassembly of the package (Hua et al., 2021). Although there are no large-scale remanufacturers, remanufactured items can be 40% less expensive than new products (Foster et al., 2014).

The repurposing process requires reconfiguring the battery pack structure and setting up new hardware and software for non-vehicle applications. It also means that the spent battery of an electric vehicle can be reused in other less stressed hardware as a secondary usage throughout its lifetime following hardware and software modifications (Hua et al., 2021).

However, reusing lithium batteries in electric vehicles still faces a number of challenges. DeRousseau et al. (2017) claimed that the secondary life offered by repurposing is difficult to realise economically due to the fall in the cost of brand-new lithium batteries. Besides, Lai et al. (2022) pointed out that lithium batteries may leak during disassembling for secondary use if not properly handled by workers. Overall, reuse methods for lithium batteries are still in their infancy. Moreover, neither accurate data nor large-scale implementation is available to determine their impact on the environment (Melin, 2019).

3.7 Environmental Impacts from the Recycling Phase Perspective

3.7.1 Pre-Treatment Processes

A pre-treatment process is required before recycling lithium batteries. This process separates the different components of lithium batteries in a safe manner. Pre-treatment processes can improve recovery efficiency and reduce the energy consumption of subsequent recovery processes (Kim et al., 2021). Figure 6 depicts the pre-treatment sequence for lithium batteries. The pretreatment process consists of seven distinct steps: Discharge, Dismantling, Comminution, Classification, Separation, Dissolution, and Thermal treatment. Discharge simply means that the remaining capacity of the lithium battery must be discharged before the spent lithium batteries are dismantled in order to avoid the potential risk of spontaneous combustion or short circuit. Dismantling involves the manual dismantling of individual spent batteries using a knife and saw (Kim et al., 2021). After dismantling, the spent LIBs must be shredded and crushed in order to liberate the electrode materials (Comminution step). Classification involves crushing the remaining lithium battery waste in a crusher equipped with a set of rotating and fixed blades. Three different size sieves of 106 Am, 200 Am, and 850 Am can be used to separate the primary shredded material according to particle sizes (Shin et al., 2005). However, a further stage of magnet separation may be required if the sorted particles still contain a large amount of iron (Shin et al., 2005). The separation method takes places immediately after sorting the three different particle sizes. In this process, the cathodes and aluminium collectors, anodes, steel shells, and plastic packages of the lithium battery sex material are separated using finer separation methods such as magnetic, eddy current, electrostatic, gravity separation, and froth flotation (Shin et al., 2005). Dissolution is the process of separating the released active material from the current collector of a used lithium battery. The cathode active material is separated from the aluminium foil using NMP solvent and ultrasonic treatment. The goal of thermal treatment is to release the electrode material by removing the immobilised active material and carbon conductive agents on the current collector (Kim et al., 2021).

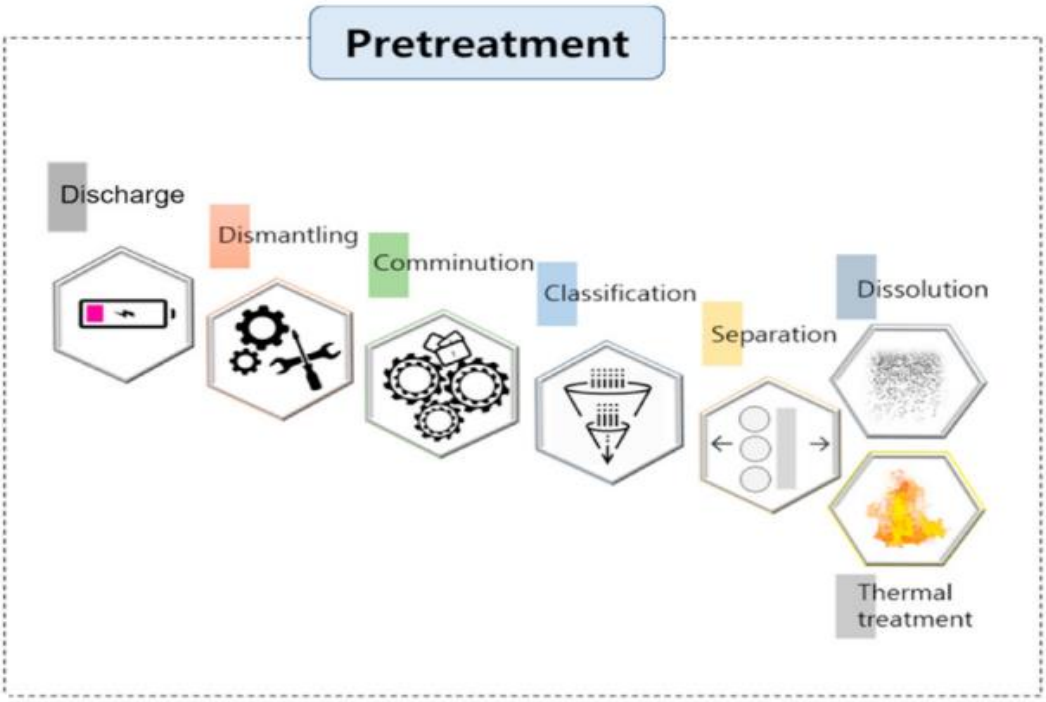

Figure 6. The pretreatment process in the LIB recycling (Source: Shin et al., 2005)

3.7.2 Recycling Methods

In order to understand the environmental impact of lithium batteries in electric vehicles during the recycling process, it is necessary to understand the three main recycling processes of lithium batteries. According to Beaudet et al. (2020), the recycling processes for lithium batteries are pyrometallurgy, hydro-metallurgy, and direct recycling. These processes are not independent of one another but must be used in tandem (Melin, 2019).

(1) Pyrometallurgy

The raw materials for lithium batteries are first burned off at high temperatures (1500 °C) in order to remove all carbon-based compounds while the remaining metals will eventually form an alloy rich in Co, Ni, and Mn. The individual elements are further recovered from these alloys using the Hydrometallurgy process. This process reduces the processing time of spent batteries as it avoids crushing and other pre-processing steps (Larouche et al., 2018). During the treatment process, the organic matter of the battery will decompose heavy metal elements such as electrolytes, graphite, steel, aluminium, and lithium. These elements are generally lost as slag or exhaust gas. Therefore, it is necessary to increase the purification process and recovery equipment in order to absorb and purify harmful gases as well as prevent secondary pollution (JIANG et al., 2018).

(2) Hydrometallurgy

The Hydrometallurgy process involves crushing and dissolving waste batteries, using suitable chemicals to selectively separate the metal elements in the leaching solution to yield a high-grade cobalt metal or lithium carbonate, and then directly recycling all of the metal elements (JIANG et al., 2018). As shown in Figure 7 depicts the procedures of the Pyrometallurgy and Hydrometallurgy processes.

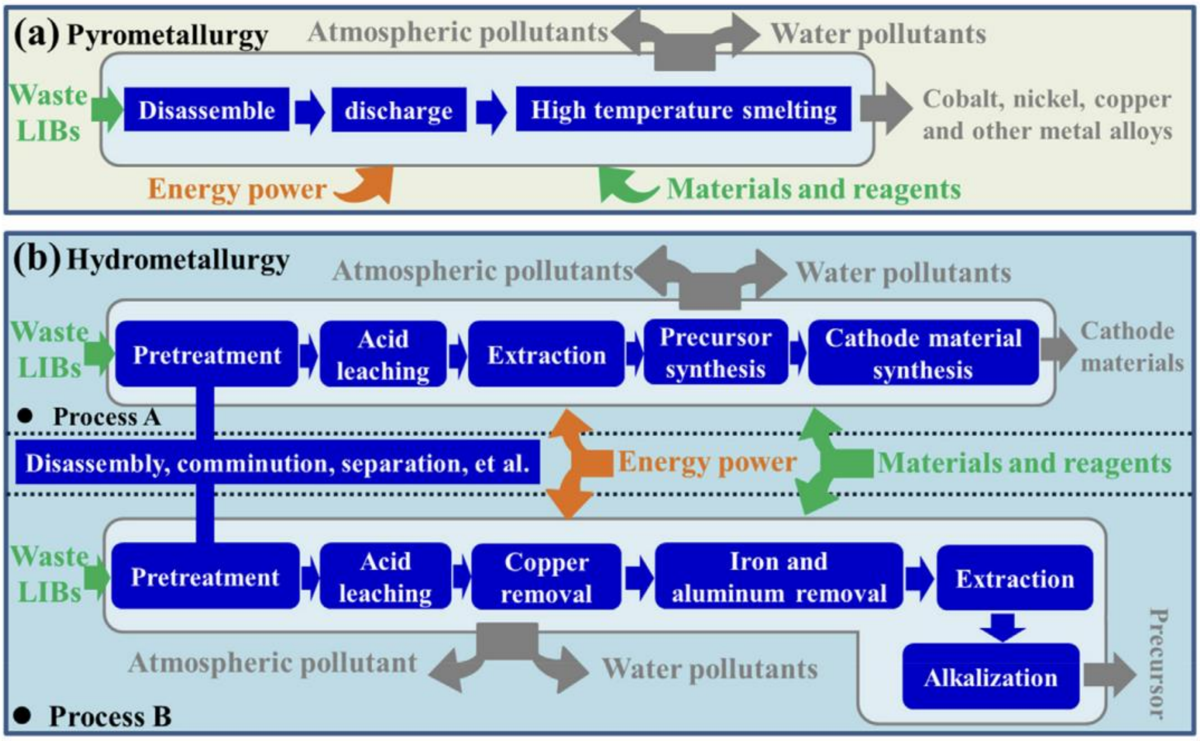

Figure 7. Flowchart of Pyrometallurgy and Hydrometallurgy (Source: Lai, 2022)

(3) Direct Recycling

EOL cathode materials that were obtained by physical or chemical methods can be recycled directly. After a post-processing process, the cathodic active material can be restored to its original structure and composition (Yang, 2020). The direct recycling process preserves the structure, morphology, and purity of the cathode material in order to restore the initial properties and electrochemical capacity of the cathode active material without decomposing into substituent elements. This allows the cathode active material to be directly reused in the manufacture of new lithium batteries (Larouche et al., 2018). Various methods for remanufacturing lithium batteries have been developed through direct recycling, including the application of high-frequency ultrasound on the entire undamaged cell, leaching processes, thermal re-functionalization processes, hydrothermal liquefaction methods, etc. (Larouche et al., 2018). Figure 8 presents the process flow chart of direct recycling. This process includes electrolyte extraction, electrode acquisition, healing treatment of cathode material, and the manufacture of lithium-ion batteries using recycled materials (Sloop et al., 2020). However, employing direct recycling to reproduce lithium batteries is time-consuming and may take up to 15 years. The recycled product may be outdated after it is reintroduced to the market (Beaudet et al., 2020).

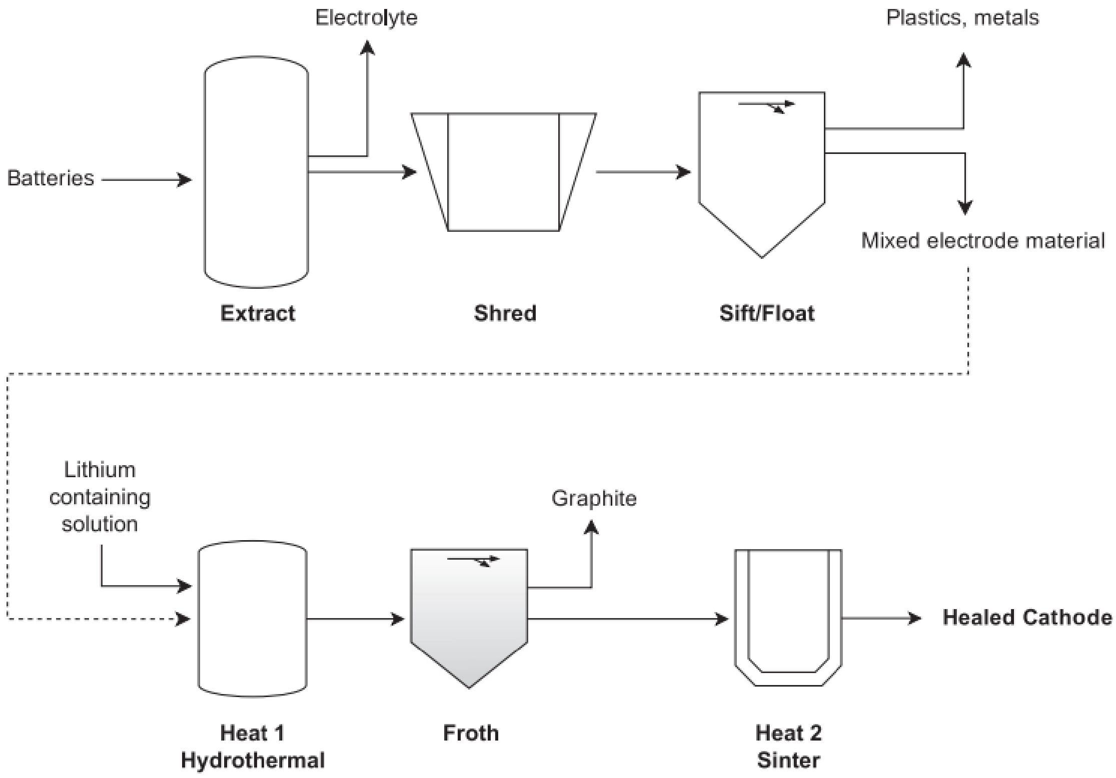

Figure 8. Direct recycling processes (Source: Sloop et al., 2020)

The above three methods are the most widely used technologies for recycling lithium batteries worldwide. Table 4 provides a visual overview of the advantages and disadvantages of the three methods. As shown in the Table, there are still a variety of alternative battery recycling solutions available. Therefore, it is important to understand the current reality of companies recycling.

Table 4. Three main recycling processes (Source: Beaudet et al., 2020)

Recycle Method	Advantages	Disadvantages
Pyrometallurgy	● Guarantees remarkable metal recovery ● No requirement for sorting or additional mechanical pre-treatment	● Excludes recycling of Li, Al, or organic materials ● Costly gas clean-up measures are essential to prevent the release of toxic air pollutants ● Demands significant energy and capital investment
Hydrometallurgy	● Guarantees exceptional metal recovery rates while maintaining energy efficiency ● No air emission ● Capability to attain high product purity	● Battery cells must be crushed, which poses safety concerns ● Acidic substances can degrade the cathode structure. ● A large volume of process effluents requires treatment, recycling, or proper disposal
Direct recycling	● Retains valuable cathode structure ● Practically all battery components such as anode, electrolyte, and foils, can be effectively recovered ● Promoting energy efficiency ● Highly convenient for recycling scraps	● Recovered materials may not match the performance of virgin materials or might become obsolete before their introduction into market ● Combining cathode materials could diminish the value of the recycled product

3.7.3 Environmental Impacts from a Recycling Perspective

Recycling lithium batteries raises both health and environmental concerns. Usually, shredding is typically the initial step during the recycling of lithium batteries (Grützke et al., 2015). After shredding, some rust may be observed on storage cans of lithium batteries. This is because lithium batteries tend to emit a black substance including lithium and manganese after shredding. The shredded battery materials also contain a toxic, hazardous, and corrosive mixture of other harmful substances such as alkyl fluorophosphate and acid. Workers must store the broken lithium battery recycling materials in inert plastic cans at room temperature or in a cool environment to prevent corrosion, environmental damage, and health hazards to humans (Grützke et al., 2015).

All three current methods of recycling lithium batteries have some environmental impact. Pyrometallurgy is a high-temperature, energy-intensive process that emits greenhouse gases and produces toxic gases or hazardous slag that require landfilling. In addition, the slag produced at high temperatures contains hazardous substances such as alkyl fluorophosphate and HF (Mrozik et al., 2021). According to the Agency for Toxic Substances and Disease Registry, fluoride such as alkyl fluorophosphate can enter nearby soil, water, and food when released into the air (ATSDR, 2014). If ingested by humans, they can affect dental health and reduces the strength of bones, which may lead to fracturing. Thus, it is important to dispose of the waste generated by pyrometallurgy.

In contrast, Mrozik et al. (2021) argue that hydrometallurgy produces much less greenhouse gas emissions since it involves solution leaching or acid leaching (Figure 7). Therefore, additional wastewater treatment is required to ensure that the leached wastewater does not contaminate the environment. Mohr et al. (2020) also claimed that both pyrometallurgy and hydrometallurgy recycling methods have environmental impacts. In their study, they compared the environmental impact of pyrometallurgy and hydrometallurgy in the recycling process. Results show that pyrometallurgy performs significantly worse than hydrometallurgy due to its high energy consumption and lack of lithium recovery. Rajaeifar et al. (2021) also compared the greenhouse gas emissions of pyrometallurgy and hydrometallurgy using two different scenarios and found comparable results. As shown in Figure 9, Scenario 1 and Scenario 2 were conducted on DC plasma smelting technology and commercially proven ultra-high temperature (UHT) furnaces, respectively. The pyrometallurgy process generates a global warming potential of up to 2350 CO_2 and 2570 CO_2 for Scenario 1 and Scenario 2, respectively. These values were much higher than that of the hydrometallurgy process. Thus, the individual results indicate that the pyrometallurgy process produces far more greenhouse gas emissions than the hydrometallurgy process.

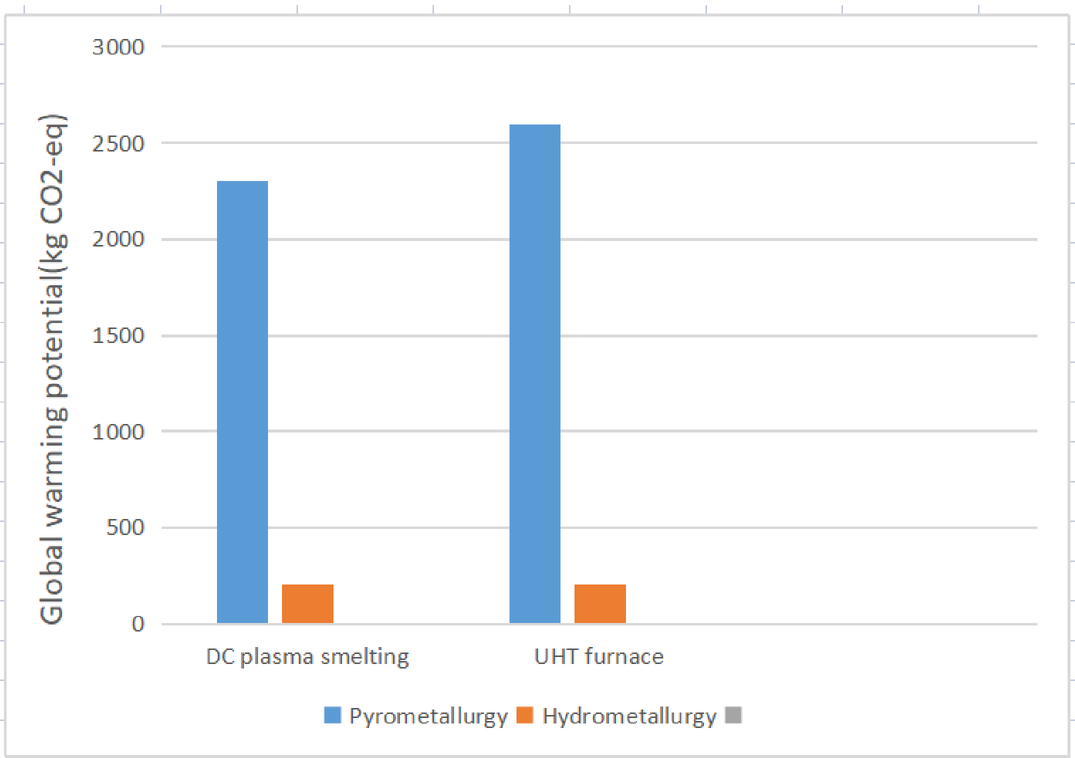

Figure 9. GHG emissions from pyrometallurgy and hydrometallurgy process using two technologies (Source: Rajaeifar et al., 2021)

However, direct recycling is still in its early stages. Therefore, there is a lack of specific data to support the claim that direct recycling is harmful to the environment (Mrozik et al., 2021). As opposed to pyrometallurgy, it is well known that direct recycling of lithium batteries can reduce GHG emissions and SO_x (Dunn et al., 2015).

3.7.4 The Future Challenge

Although lithium batteries for recycling electric vehicles have many advantages, they still encounter a lot of challenges.

Firstly, collecting spent lithium batteries is expensive and involves different sectors, including value chains; producers, sellers, governments, waste managers, and consumers (Larouche et al., 2020). The high cost leads to the low recovery rate of waste lithium batteries worldwide. Secondly, about 20% of spent lithium batteries are still exported to Europe for use as second-hand or used appliances, which makes it even harder to recycle spent lithium batteries (Eucobat, 2020). More importantly, the global recycling rate of lithium batteries is low. For example, the recycling rate in North America is estimated to be around 5% (Kincaide, 2019).

Secondly, the cathode materials have been upgraded from lithium-cobalt oxide (LCO) to lithium-nickel-manganese-cobalt (NMC), lithium-manganese oxide (LMO), lithium-iron-phosphate(LFP), nickel-aluminum-oxide(NCA), and lithium-iron-phosphate (LFP) due to the continuous development of lithium batteries. The diverse development of materials for LIBs can pose a challenge to recyclers. Recyclers must not only investigate new recycling technologies but also consider the safety issues attached to recycling (Larouche et al., 2020).

Furthermore, the fierce competition among battery recyclers and the falling price of new lithium batteries have limited the profit margins of recyclers, thus weakening the viability of the recycling industry (Larouche et al., 2020).

3.8 Environmental Impacts from the Disposal Phase Perspective

Currently, the primary method of disposal for lithium batteries is landfilling (Mrozik, 2021). Leachate from open dumps contains concentrations of organic carbon, ammonia, chlorides, and heavy metals. Therefore, improper treatment of waste can easily lead to metal leakage from landfills, dissolution of contaminants into water bodies, and contamination of soil and groundwater (Ferronato & Torretta, 2019). The composition of lithium batteries is shown in Table 5 (Rahman et al., 2017). Lithium batteries are disposed of in landfills. Leachable metals like cobalt, nickel, and lithium may leak out If the casing chemically degrades in the landfill or is destroyed during compaction, resulting in heavy metals contamination of the groundwater or nearby soil (Winslow et al., 2018). According to Zand and Abduli, (2008), Iran has imported nearly 10,000 tonnes of batteries over the last decade. Most of these items are discarded in municipal solid waste without any separation and sent to sanitary landfills, resulting in leachate infiltration and groundwater contamination near municipal landfills. Furthermore, improper treatment of lithium batteries in landfills can produce air pollutants, which can contribute to climate change and the greenhouse effect. This is because lithium battery emissions can react with other air pollutants to form photochemical smog, which can result in the production of toxic compounds, including ozone, other unhealthy gases, and particles that can have an adverse impact on both the environment and human health (Ashok et al., 2021). Furthermore, the metal molecules that lithium batteries release into the atmosphere can cause acidic deposits that destroy the soil and animal habitats. In addition, damaged LIBs can cause landfill fires if they are disposed of in landfills. This is due to the possibility that the lithium batteries have not been fully depleted and still contain residual energy, or the flammable metals in the lithium batteries have leaked and mixed with other components, causing spontaneous combustion. Polycyclic aromatic hydrocarbons, dioxins/furans, volatile organic compounds, heavy metals, PCBs or organochlorine pesticides, and PM2.5 are among the harmful gases and smoke that these types of fires often produce (Mrozik et al., 2021). Thus, landfill fires caused by batteries not only produce a range of gases that pollute the environment but also spread particulates and harmful chemicals farther away due to smoke. This situation is persistent. According to the report by the Environmental Services Association (ESA), 1,125 (25%) of the 4,500 landfill fires in the UK between 2017 and 2018 were caused by lithium batteries (ESA, 2020).

Thus, the rational way to handle lithium batteries is to recycle and reuse them. However, about 53%, 79%, and 94% of solid waste are disposed of in landfill in the USA, China, and Malaysia, respectively (Mrozik et al., 2021). This solid waste contains about 4% electronic waste, including lithium batteries. This is due to the low global battery recycling rates caused by the lack of regulation on lithium battery recycling in most countries and the lack of recycling infrastructure (Karnchanawong & Limpiteeprakan, 2009). As a result, most lithium batteries are not recycled but rather dumped in landfill.

Table 5. Composition of lithium batteries (Source: Rahman et al., 2017)

Components	Amount (%)
Cathode, Anode, and Electrode	46.2

Plastic case	18.63
Steel case	10.56
Copper barrel	7.5
Aluminum foil	1.8
Electrical board and circuit	2.75
Others	12.56

4. Discussion

The previous section has shown that it is possible to determine the emissions and pollution caused by LIBs from the cradle to the grave using LCA as a framework for literature review (as shown in Figure 2). Thus, lithium batteries used in electric vehicles have a negative impact on the environment, which raises environmental concerns.

However, a literature review on LCA in lithium batteries for electric vehicles reveals some shortcomings in the current LCA, which can be summarised as follows: (i) Although many types of selective disposal are currently available for spent lithium batteries, landfills are still the major disposal option, (ii) Recycling of spent LIBs remains the current challenge, (iii) The definition of LCA is confusing and differs from some traditional definitions or concepts, (iv) This dissertation faces some limitations, including limited literature review and the limited data.

4.1 Selective Treatment of Spent Lithium Batteries

The best way to dispose of spent lithium batteries is to recycle and remanufacture them. However, Chapter 3.8 revealed that the majority of lithium battery waste is still dumped in landfills globally. Most people dispose of lithium batteries as Municipal Solid Waste (MSW) unless due to the regional ban on hazardous waste (Smith & Gray, 2010). Even though lithium batteries are considered hazardous waste, countries like the United States still manage them as ordinary solid waste (Winslow et al., 2018). As a result, the vast majority of lithium batteries are not managed as waste streams, rendering lithium batteries indistinguishable from ordinary waste. However, the environment may suffer greatly if lithium batteries are disposed of as MSW in landfills or incinerated at high temperatures in incinerators. If lithium batteries are disposed of in landfills, they can easily lead to metal leakage and contaminants dissolving into the water column. The hazards are explained in detail in Chapter 3.8. Burning lithium batteries as MSW in incinerators at high temperatures can also have serious environmental consequences. According to Jeong et al. (2006), the incinerator can be used to incinerate spent lithium batteries. After treatment at incineration plants, flame retardants and combustible powders from waste lithium batteries are discharged into the atmosphere and water systems.

The impact of carbon dioxide from the incineration process and copper emissions to the atmosphere and water systems account for 89.3% of the environmental load on human health and ecosystem health when LIBs waste is incinerated. Therefore, the environmental impact of spent lithium batteries would worsen if a country does not prioritise recycling and remanufacturing lithium batteries while ignoring the waste stream management of lithium batteries.

4.2 Current Challenge of Recycling Spent LIBs

The current literature lacks consideration of the recycling value chain of lithium batteries. The available literature does not mention in detail the construction of recycling networks and sorting technologies (Arshad et al., 2022). Spent lithium batteries lack special recycling stations, recycling bins, and collection systems. Most of these facilities are co-located with other waste and disposed of jointly. Given that spent lithium batteries are currently not sorted according to type, size and chemical composition, sorting technology is still in its infancy and recycling efficiency is low. Additionally, the lack of standardisation in the development of lithium batteries and the rapid iteration of lithium batteries over time have prevented recyclers from having the right technology to handle different types of lithium batteries. It also shows that the recyclability of lithium batteries was not considered during the original design process.

4.3 Unclear Definition of LCA

One major concern is the ambiguity surrounding the definition of lithium batteries for electric vehicles in the LCA. Consideration must be given to the definition of reuse of spent lithium batteries. According to the traditional definition, reuse refers to a product that is intended to be used repeatedly and includes direct reuse, reuse after cleaning or lubricating the product, reuse after repairing a fault, and reuse by redeployment elsewhere (Nibusinessinfo, n.d.). According to DeRousseau et al. (2017), the current ways of reusing spent lithium batteries are remanufacturing and repurposing. Remanufacturing is the process of repairing or refurbishing EV battery packs for redeployment while repurposing involves using EOL LIBs for less burdensome, secondary applications such as backup power and power tools. This illustrates the difference between the reuse of lithium batteries and the conventional reuse. If the LCA method for lithium batteries in electric vehicles does not regulate the exact meaning and operation of each definition, it can be challenging to ensure that the same definition expresses the same meaning across different literary works.

4.4 Limitations

4.4.1 Limited Literature

This dissertation focuses on the global lithium battery for electric vehicles and therefore the collection has a global scope. The dissertation is based on the LCA method from Candle to the Grave. As part of the literature evaluation, the most representative literature will be collected at each phase of LCA. As a result, the entire LCA phase is based on the collection of studies from different countries. Therefore, this dissertation does not focus on the full LCA phase in a particular country but rather examines the global trends of lithium batteries for electric vehicles. Overall, it can be concluded that lithium batteries for electric vehicles pose an environmental concern. Given that the literature review covers a period from 2005 to 2022, there may be controversy over some lithium battery technologies. Early literature from 2006 used incinerators to incinerate lithium batteries for electric vehicles, which had a negative impact on the environment. However, it is doubtful whether today's technology can resolve this problem. Given that all lithium batteries are still in the development stage and there are many opportunities for technological advancement, it is worthwhile to explore whether the treatment stage of used lithium batteries has room for future development.

The current confusing development of the LCA for lithium batteries in electric vehicles is of significant concern. When examining the LCA method for EV lithium batteries in a certain country or region, there will be unequal or inconsistent data due to their diverse technologies. In addition, the above-mentioned terminology for the LCA of lithium batteries for electric vehicles lacks standardisation. Therefore, the future direction of the LCA method for lithium batteries in electric vehicles now focuses on how to unify the global development of lithium batteries and specify the terminology of lithium batteries on LCA.

4.4.2 Limited Data

Given that lithium batteries are still in the development phase, there is a dearth of literature on the LCA method for lithium batteries in electric vehicles. According to Mrozik et al. (2021), it is challenging to find data on the environmental impact of recycling LIBs because recycling LIBs is still in its early phase. Therefore, it is impossible to obtain full data in the current research, signifying that some data were not readily available for analysis and comparison. This makes it impossible to directly summarise any piece of literature while searching and analysing specific data on emissions during the production and recycling of lithium batteries. In Chapter 3.2, the pollutant data on the production of lithium batteries were derived from a case study conducted in a Chinese lithium battery facility by Wang (2019). Besides, there is a lack of direct comparison between Pyrometallurgy and Hydrometallurgy in the current literature. Therefore, it is crucial to adopt the DC plasma smelting and UHT furnace methods to determine the emissions and analysis of recycling methods (Rajaeifar et al., 2021). Additionally, the limitation of these methods is that production and recycling practises may differ between nations, making it difficult to ensure that the data will function or be accurate in every country.

Even though the process of transporting lithium batteries has been established as one of the major problems causing environmental pollution, the European Environment Agency does not provide specific data and in-depth discussion on the emissions caused by transport. According to existing data, road travel accounts for only 70% of greenhouse gas emissions. The European Environment Agency makes no recommendations on the greenhouse gas emissions from transportation. When operating electric vehicles, many authors have discussed the indirect emissions of lithium batteries and directly quote the lithium battery energy efficiency as 95% (Ellingsen, 2014). Ellingsen (2016) also discussed the indirect emissions data of lithium batteries after 180,000 km of electric vehicle exercise. Given that Ellingsen's literature was published nearly seven years ago as well as the increasing growth of electric vehicles and lithium batteries, it is difficult to compare these old data with recent ones.

5. Recommendation

In summary, different recommendations are to address the issues raised in the Discussion section. The first issue is the lack of uniform data on lithium batteries for electric vehicles. The second issue is the unclear definition of the LCA method for EV lithium batteries. The third issue is the low recycling rate of lithium batteries, the lack of waste stream management, and the extensive amount of spent lithium batteries that are disposed of in landfills or burned in incinerators.

(1) Lack of Uniform Data on EV Lithium Batteries

Firstly, there must be systematic data collection from different countries to ensure the accuracy and consistency of data sources. If data sharing across different documents is required, a data-sharing platform must be established to achieve uniformity and sharing of data. In addition, data governance and management should be strengthened to ensure data authenticity and consistency. At the same time, policies and regulations should be established to avoid data plagiarism or data falsification.

(2) The Definition of the LCA Approach for Lithium Batteries in Electric Vehicles Is Unclear

In accordance with international organisations, different countries should develop uniform LCA standards and guidelines for lithium batteries in an electric vehicles in order to ensure that different countries and companies adopt the same assessment methods. Furthermore, the LCA data for lithium batteries in the literature should be open and transparent to ensure the authenticity of the assessment results.

(3) Low Recycling Rate and Lack of Waste Stream Management for Lithium Batteries

Firstly, modern automation and artificial intelligence technologies can be used in lithium battery recycling to address the costly parts of the recycling value chain, such as collecting, transporting, sorting, and storing spent lithium batteries. Besides, companies should implement designs for the direct recyclability of lithium batteries. Companies can modularise the different components of lithium batteries, allowing recyclers to simply disassemble them and then directly recycle the metal they require. In addition, the government can also implement special recycling sites, recycling bins, and collection systems to collect different types of lithium batteries. It can also ban the disposal of lithium batteries with general waste, designating them as hazardous waste that requires special treatment. In addition, the government can provide financial incentives to encourage more enterprises to participate in the lithium battery recycling project rather than disposing of used lithium batteries in landfills. Moreover, the government can enhance publicity and public education to raise awareness of the importance of recycling spent lithium batteries. This can be accomplished through advertisements, publicity campaigns, and educational courses that inform people of the impact of used batteries on the environment and health, as well as how to properly recycle and dispose of the waste.

6. Conclusions

In conclusion, this thesis provides a literature review of lithium batteries for electric vehicles using the life cycle assessment method. It also presents a comprehensive understanding of the cradle-to-grave emissions and pollution of lithium batteries for electric vehicles. In particular, the mining of raw materials for lithium batteries produces carbon dioxide and harmful electrolyte emissions. The production of lithium batteries causes water pollution, air pollution, and solid waste emissions. The transportation and distribution of lithium batteries can emit gaseous pollutants, volatile organic compounds, nitrogen oxides, heavy metals, organic pollutants, and particulate matter. Spent lithium batteries can cause carbon emissions and CO_2 equivalent emissions. For instance, the pyrometallurgy method of recycling lithium batteries can cause high temperatures, high energy consumption, greenhouse gases, and toxic substances. On the other hand, the Hydrometallurgy method produces less environmental pollution. When lithium batteries are disposed of in landfills heavy metals can leach out and damage neighbouring soil or groundwater. Furthermore, lithium battery emissions in landfills can react with other air pollutants to form photochemical smog. In addition, damaged lithium batteries in landfills can cause landfill fires. Therefore, it is evident that lithium batteries for electric vehicles currently have a negative impact on the environment and are of significant concern.

In the process of searching the literature, the following problems were discovered: (i) lack of unified data on lithium batteries for electric vehicles, (ii) unclear definition of the LCA method for lithium batteries in electric vehicles, (iii) low recycling rate of lithium batteries and lack of waste stream management, (iv) a wide time span in the literature on lithium batteries for electric vehicles and (v) controversies in the technology. In response to the aforementioned issues, the following recommendations are provided: (i) Different countries must develop a clear data collection to ensure the accuracy and consistency of data sources, (ii) In accordance with international organisations, different countries must develop a uniform LCA standards and guidelines for electric vehicle lithium batteries, (iii) Advanced automation and artificial intelligence technologies can be used to address the costly parts of the recycling value chain, (iv) Companies can modularise the different components of lithium batteries, (v) Governments must implement dedicated recycling sites, bins and collection systems to specifically collect different types of lithium batteries, (vi) The government must provide financial incentives to encourage the participation of more companies in the recycling of lithium batteries, (vii) The government needs to do more to educate the public and create awareness of the need to recycle spent lithium batteries, (viii) There is need to regularly update the literature.

Reference

Agency for Toxic Substances and Disease Registry, (2014). ToxFAQs™ for Fluorides, Hydrogen Fluoride, and Fluorine. https://wwwn.cdc.gov/TSP/ToxFAQs/ToxFAQsDetails.aspx?faqid=211&toxid=38.

Arshad, F., Lin, J., Manurkar, N., Fan, E., Ahmad, A., Wu, F., & Li, L, (2022). Life cycle assessment of lithium-ion batteries: a critical review. *Resources, Conservation and Recycling*, *180*, 106164.

Ashok, K., Babu, M., Jula, V., & Mullai, N. K, (2021). Impact of used battery disposal in the environment. *Linguistics and Culture Review*, *5*(S1), 1276-1286.

Beaudet, A., Larouche, F., Amouzegar, K., Bouchard, P., & Zaghib, K, (2020). Key challenges and opportunities for recycling electric vehicle battery materials. *Sustainability*, *12*(14), 5837.

Canalys, (2020). Global electric vehicle market 2020 and forecasts. https://www.canalys.com/newsroom/canalys-global-electric-vehicle-sales-2020.

Chen, Q., Lai, X., Gu, H., Tang, X., Gao, F., Han, X., & Zheng, Y, (2022). Investigating carbon footprint and carbon reduction potential using a cradle-to-cradle LCA approach on lithium-ion batteries for electric vehicles in China. *Journal of Cleaner Production*, *369*, 133342.

Dunn, J. B., Gaines, L., Kelly, J. C., James, C., & Gallagher, K. G, (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science*, *8*(1), 158-168.

Eftekhari, A, (2017). Energy efficiency: a critically important but neglected factor in battery research. *Sustainable Energy & Fuels*, *1*(10), 2053-2060.

Ellingsen, L. A. W., Hung, C. R., & Strømman, A. H, (2017). Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment*, *55*, 82-90.

Ellingsen, L. A. W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., & Strømman, A. H, (2014). Life cycle assessment of a lithium-ion battery vehicle pack. *Journal of Industrial Ecology*, *18*(1), 113-124.

Ellingsen, L. A. W., Singh, B., & Strømman, A. H, (2016). The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. *Environmental Research Letters*, *11*(5), 054010.

Environmental Services Association, (2020). ESA to launch battery recycling campaign in bid to reduce waste fires. http://www.esauk.org/application/files/2615/9783/3646/PRESS_RELEASE_Take_Charge_Campaign_v1.pdf.

Ferronato, N., & Torretta, V, (2019). Waste mismanagement in developing countries: A review of global issues. *International journal of environmental research and public health*, *16*(6), 1060.

Grützke, M., Krüger, S., Kraft, V., Vortmann, B., Rothermel, S., Winter, M., & Nowak, S, (2015). Investigation of the Storage Behavior of Shredded Lithium-Ion Batteries from Electric Vehicles for Recycling Purposes. *ChemSusChem*, *8*(20), 3433-3438.

Hannan, M. A., Hoque, M. M., Hussain, A., Yusof, Y., & Ker, P. J, (2018). Lithium-ion batteries' state-of-the-art and energy management system in electric vehicle applications: Issues and recommendations. *Ieee Access*, *6*, 19362-19378.

Hannah, R, (2020). Cars, planes, trains: where do CO2 emissions from transport come from? https://ourworldindata.org/co2-emissions-from-transport.

Hansen, W., Christopher, M., & Verbuecheln, M, (2002). EU Waste Policies and Challenges for Local and Regional Authorities. http://ecologic.eu/sites/files/download/projekte/1900-1949/1921-1922/1921-1922_background_paper_waste_en.PDF.

Hao, H., Mu, Z., Jiang, S., Liu, Z., & Zhao, F, (2017). GHG Emissions from the production of lithium-ion batteries for electric vehicles in China. *Sustainability*, *9*(4), 504.

How, D. N., Hannan, M. A., Lipu, M. H., & Ker, P. J, (2019). State of charge estimation for lithium-ion batteries using model-based and data-driven methods: A review. *Ieee Access*, *7*, 136116-136136.

Hu, Y., Jin, Y., & Zhang, S, (2021). Climate and health impacts and social costs of electric vehicles replacing fuel vehicles—a cost-effectiveness analysis from a single-vehicle perspective. Journal of Peking University: Natural Science Edition, 57(5), 11.

Hua, Y., Liu, X., Zhou, S., Huang, Y., Ling, H., & Yang, S, (2021). Toward sustainable reuse of retired lithium-ion batteries from electric vehicles. Resources, Conservation and Recycling, 168, 105249.

IEA, (2022). International Shipping. https://www.iea.org/reports/international-shipping.

Jeong, S. J., Lee, J. Y., Sohn, J. S., & Hur, T, (2006). Life cycle assessments of long-term and short-term environmental impacts for the incineration of spent Li-ion batteries (LIBs). *Applied Chemistry for Engineering*, *17*(2), 163-169.

Jiang, H., Chen, Y., & Liu, Y, (2018). International lithium-ion battery recycling technology route and enterprise overview. *New materials industry*, (3), 5.

Kang, D. H. P., Chen, M., & Ogunseitan, O. A, (2013). Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environmental science & technology*, *47*(10), 5495-5503.

Karnchanawong, S., & Limpiteeprakan, P, (2009). Evaluation of heavy metal leaching from spent household batteries disposed in municipal solid waste. *Waste Management*, *29*(2), 550-558.

Kim, H. C., Wallington, T. J., Arsenault, R., Bae, C., Ahn, S., & Lee, J, (2016). Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis. *Environmental science & technology*, *50*(14), 7715-7722.

Kim, S., Bang, J., Yoo, J., Shin, Y., Bae, J., Jeong, J., & Kwon, K, (2021). A comprehensive review on the pretreatment process in lithium-ion battery recycling. *Journal of Cleaner Production*, *294*, 126329.

Kincaide, J, (2019). Where Are Batteries Ending Up Now? *Proceedings of the NaatBatt Lithium-ion Battery Recycling Workshop*, Buffalo, NY, USA, 9-10.

Klopffer, W., & Birgit, G, (2014). *Life Cycle Assessment (LCA)*. Wiley-VCH Verlag GmbH & Co. KGaA. pp. 1-2.

Klyshko, N., & Mikhailova, A, (2019). Comparison of Electric Vehicle Batteries: NCA VS LFP. *Редакционная коллегия*, 142.

Larouche, F., Demopoulos, G. P., Amouzegar, K., Bouchard, P., & Zaghib, K, (2018). Recycling of Li-ion and Li-solid state batteries: the role of hydrometallurgy. *In Extraction 2018: Proceedings of the First Global Conference on Extractive Metallurgy* (pp. 2541-2553). Springer International Publishing.

Larouche, F., Tedjar, F., Amouzegar, K., Houlachi, G., Bouchard, P., Demopoulos, G. P., & Zaghib, K, (2020). Progress and status of hydrometallurgical and direct recycling of Li-ion batteries and beyond. *Materials*, *13*(3), 801.

Marques, P., Garcia, R., Kulay, L., & Freire, F, (2019). Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. *Journal of Cleaner Production*, *229*, 787-794.

Matthew, E., & Sarah, N, (n.d.). Life Cycle Assessment Explained. https://stich.culturalheritage.org/life-cycle-assessment-explained/.

McManus, M.C, (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Appl. Energy*, *93*, 288-295. https://doi. org/10.1016/j.apenergy.2011.12.062.

Melin, H. E, (2019). State-of-the-art in reuse and recycling of lithium-ion batteries — A research review. *Circular Energy Storage*, *1*, 1-57.

Meshram, P., Mishra, A., & Sahu, R, (2020). Environmental impact of spent lithium-ion batteries and green recycling perspectives by organic acids — A review. *Chemosphere*, *242*, 125291.

Mohr, M., Peters, J. F., Baumann, M., & Weil, M, (2020). Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. *Journal of Industrial Ecology*, *24*(6), 1310-1322.

Mrozik, W., Rajaeifar, M. A., Heidrich, O., & Christensen, P, (2021). Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy & Environmental Science*, *14*(12), 6099-6121.

National Transportation Safety Board (NTSC), (2007). Accident report: in flight cargo fire United Parcel Service Co. Flight 1307 McDonnell Douglas DC-8-71F, N748UP, Philadelphia, PA, (NTSB/AAR-07/07 PB2007-910408). Washington DC. Electronic reference, http://www.ntsb.gov/publictn/2007/AAR0707.pdf (Accessed: 28.10.10).

Petrauskienė, K., Skvarnavičiūtė, M., & Dvarionienė, J, (2020). Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. *Journal of Cleaner Production*, *246*, 119042.

Rahman, A., Afroz, R., & Safrin, M, (2017). Recycling and Disposal of Lithium Battery: Economic and Environmental Approach. *IIUM Engineering Journal*, *18*(2), 238-252.

Rajaeifar, M. A., Raugei, M., Steubing, B., Hartwell, A., Anderson, P. A., & Heidrich, O, (2021). Life cycle assessment of lithium-ion battery recycling using pyrometallurgical technologies. *Journal of Industrial Ecology*, *25*(6), 1560-1571.

Shin, S. M., Kim, N. H., Sohn, J. S., Yang, D. H., & Kim, Y. H, (2005). Development of a metal recovery process from Li-ion battery wastes. *Hydrometallurgy*, *79*(3-4), 172-181.

Sloop, S., Crandon, L., Allen, M., Koetje, K., Reed, L., Gaines, L., & Lerner, M, (2020). A direct recycling case study from a lithium-ion battery recall. *Sustainable Materials and Technologies*, *25*, e00152.

Smith, M. J., & Gray, F. M, (2010). Batteries, from cradle to grave. *Journal of Chemical Education*, *87*(2), 162-

167.

Song, J., Yan, W., Cao, H., Song, Q., Ding, H., Lv, Z., & Sun, Z, (2019). Material flow analysis on critical raw materials of lithium-ion batteries in China. *Journal of Cleaner Production*, *215*, 570-581.

Tencent.com, (2021). Timetable for the global fuel vehicle ban. https://new.qq.com/rain/a/20211217A05TJ100.

Tong, S. J., Same, A., Kootstra, M. A., & Park, J. W, (2013). Off-grid photovoltaic vehicle charge using second life lithium batteries: An experimental and numerical investigation. *Applied energy*, *104*, 740-750.

United Nations Environmental Program, (2013). Retrieved from http://www.unep.org/ietc/Portals/136/Publications/Waste%20Management/UNEP%20NWMS%20English.pdf.

Wang, Y., Yu, Y., Huang, K., & Tang, B, (2019). From the perspective of battery production: energy–environment–economy (3E) analysis of lithium-ion batteries in China. *Sustainability*, *11*(24), 6941.

Winslow, K. M., Laux, S. J., & Townsend, T. G, (2018). A review on the growing concern and potential management strategies of waste lithium-ion batteries. *Resources, Conservation and Recycling*, *129*, 263-277.

Yang, T., Lu, Y., Li, L., Ge, D., Yang, H., Leng, W., & Li, Z, (2020). An effective relithiation process for recycling lithium-ion battery cathode materials. *Advanced Sustainable Systems*, *4*(1), 1900088.

Zackrisson, M., Avellán, L., & Orlenius, J, (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles–Critical issues. *Journal of cleaner production*, *18*(15), 1519-1529.

Zand, A. D., & Abduli, M. A, (2008). Current situation of used household batteries in Iran and appropriate management policies. *Waste Management*, *28*(11), 2085-2090.

Zhang, R., Xia, B., Li, B., Cao, L., Lai, Y., Zheng, W., & Wang, W, (2018). State of the art of lithium-ion battery SOC estimation for electrical vehicles. *Energies*, *11*(7), 1820.

Zhao H, (2016). Overview of the status quo and development of electric vehicle battery. *Modern trade and industry*, *37*(33), 2.

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