

Review

A Review on Battery Market Trends, Second-Life Reuse, and Recycling

Yanyan Zhao ¹, Oliver Pohl ^{1,2}, Anand I. Bhatt ^{1,*}, Gavin E. Collis ^{3,*}, Peter J. Mahon ^{2,*}, Thomas Rüther ¹ and Anthony F. Hollenkamp ³

¹ CSIRO Energy, Research Way, Clayton, VIC 3168, Australia; yanyan.zhao@csiro.au (Y.Z.); oliver.pohl@csiro.au (O.P.); thomas.ruther@csiro.au (T.R.)

² Department of Chemistry and Biotechnology, School of Science, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, VIC 3122, Australia

³ CSIRO Manufacturing, Research Way, Clayton, VIC 3168, Australia; tony.hollenkamp@csiro.au

* Correspondence: anand.bhatt@csiro.au (A.I.B.); gavin.collis@csiro.au (G.E.C.); pmahon@swin.edu.au (P.J.M.); Tel.: +61-3-9545-8691 (A.I.B.); +61-3-9545-2458 (G.E.C.); +61-3-9214-4880 (P.J.M.)

Abstract: The rapid growth, demand, and production of batteries to meet various emerging applications, such as electric vehicles and energy storage systems, will result in waste and disposal problems in the next few years as these batteries reach end-of-life. Battery reuse and recycling are becoming urgent worldwide priorities to protect the environment and address the increasing need for critical metals. As a review article, this paper reveals the current global battery market and global battery waste status from which the main battery chemistry types and their management, including reuse and recycling status, are discussed. This review then presents details of the challenges, opportunities, and arguments on battery second-life and recycling. The recent research and industrial activities in the battery reuse domain are summarized to provide a landscape picture and valuable insight into battery reuse and recycling for industries, scientific research, and waste management.



Citation: Zhao, Y.; Pohl, O.; Bhatt, A.I.; Collis, G.E.; Mahon, P.J.; Rüther, T.; Hollenkamp, A.F. A Review on Battery Market Trends, Second-Life Reuse, and Recycling. *Sustain. Chem.* **2021**, *2*, 167–205. <https://doi.org/10.3390/suschem2010011>

Received: 11 December 2020

Accepted: 18 January 2021

Published: 9 March 2021

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Keywords: battery; end-of-life; reuse; second-life; recycling; lead-acid; nickel; lithium; lithium ion battery; policy; regulation

1. Introduction

Battery technology is ubiquitous in modern life, from portable electronics through to transportation and grid scale energy storage. The demand for batteries is still growing globally. In 2014, the battery market size was US \$62 billion [1] doubling to US \$120 billion in 2019 [2]. The global battery consumption is anticipated to increase five-fold in the next ten years [3].

Lead acid batteries (LABs), lithium-based and nickel-based batteries are dominant with a total contribution of 94.8% of the global battery market in 2016 [4]. Lithium-ion batteries (LIBs) alone are projected to reach a value of US \$53.8 billion by 2024, with a compound annual growth rate (CAGR) of 11% during 2019–2024 [5]. While the battery market is growing, the battery end-of-life (EoL) management will become a key issue in the near future.

Currently at the end-of-life, some battery chemistries are collected from waste streams because of strict government regulations (e.g., lead-acid batteries), resulting in mature recycling and resource recovery technologies. The recycling rates of LABs in the developed regions including the US and EU reach to 98~99% [6,7] compared to an approximately 80–85% recycling rate reported in China [8]. Low rates of LAB recycling in developing countries and regions have led to significant environmental and health concerns [7]. Lithium-based batteries (second largest market share) globally have yet to achieve mature reuse, recycling, and resource recovery processes. In Australia, only 6% of lithium-ion

batteries were collected for recycling in 2017–2018 [9]. In China, it is anticipated that the weightend of end-of-life (EoL) LIBs will surpass 500,000 tonnes by 2020 [10].

High rates of electric vehicle (EV) adoption during the past decade further means a large amount of the traction batteries from the first batches of EVs and hybrid EVs will soon reach EoL, joining the other types of batteries in e-waste streams. These batteries are regarded as EoL for their first use, though as discussed later a second life application may be relevant for some batteries before requiring disposal. Although some EoL batteries cannot continue to sufficiently power a designated application or a device, they still contain a significant amount of stored energy. For example, a spent EV lithium-ion battery typically contains 70–80% of the initial energy [11,12]. There is potential to utilize this remaining capacity for alternative applications before batteries ending up in waste streams. Noting that the EV battery capacity is projected to exceed 275 GWh annually by 2030 [13], if there is a viable commercial option to deploy these batteries, then issues such as stockpiling or landfill disposal (leading to environmental or health issues) may be minimized [14].

The use of batteries after they have reached the end of their first intended life is termed “second-life.” The discussions of second-life battery (SLB) mostly still stand in the conceptual realm although some notable projects have already been carried out to validate them in real life [15–20]. There are strong arguments for SLBs, where the residual energy can be recovered and directly deployed into other battery applications with lower energy requirement reducing production costs associated with using a new battery, and negative factors associated with battery collection, storage, handling, and recycling. However, there are some challenges that need to be considered and addressed for current EoL batteries. Complexities associated with non-standardized battery system design, new battery system cost reductions making SLB system pricing uncompetitive, lack of SLB quality and performance guarantees, and lack of policy, protocols or certification around the SLBs globally are the key barriers to SLBs [21]. However, utilizing SLBs has inevitably attracted attention because of its huge energy potential. For example, repurposing EV batteries has the potential to exceed 200 gigawatt hours by 2030 which represents a global value upward of \$30 billion [21]. Figure 1 presents the estimated second life EV battery supply by region and utility scale demand change between 2020 and 2030. However, second-life is only a supplementary EoL management strategy designed to be implemented before recycling. In principle, recovered material can be used for manufacturing new batteries to form a Circular Economy value chain, where recovered material costs are lower than virgin material production costs.

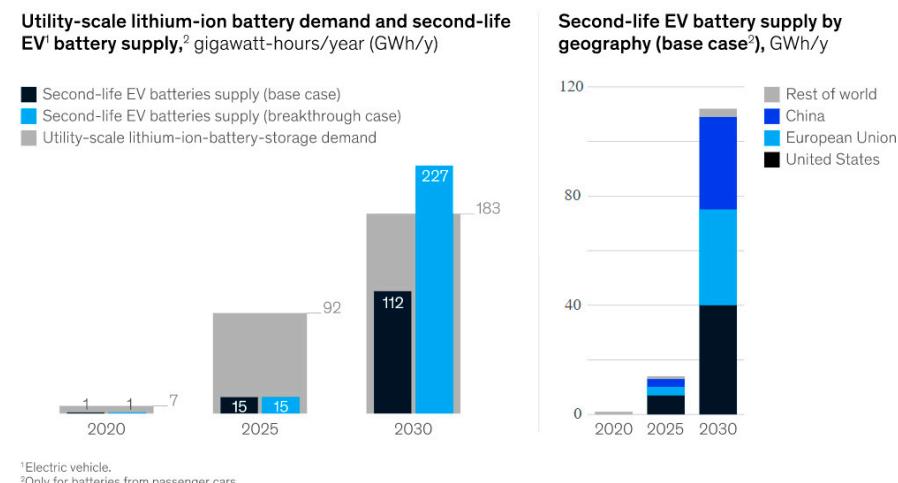


Figure 1. Estimated second-life EV battery supply by region and utility scale demand change between 2020 and 2030 by McKinsey and Company [22]. Exhibit from “Second-life EV batteries: The newest value pool in energy storage”, April 2019, McKinsey & Company, www.mckinsey.com. Copyright © 2021 McKinsey & Company. All rights reserved. Reprinted by permission.

The past decade has seen a significant increase in battery markets and a considerable number of national and international efforts by the private and public sectors have documented reviews focusing on the recycling of batteries, in particular LIBs [23]. Although the current discussion around battery reuse and recycling have been met with differing opinions, a significant number of these are around changing battery chemistries [23–27], geographical location [28], economic [24,29–35], environmental [36,37], and governmental regulations [33], materials security [38], safety and waste management regulations [39], societal benefits and globally as we transition from a linear to Circular Economy [7]. Consequently, different countries are progressing down different pathways to address their immediate challenges. In Europe the EU legislation Directive 2000/53/EC of the European Parliament and of the Council of September 2000 on EoL vehicles require that EoL vehicles should be designed in a way that they can be easily recovered, reused, and recycled. The recycling of LIBs is also encouraged by legislation in the EU where the Battery Directive 2006/66/EC was instituted. This is discussed in more details in the section below.

The focus of this paper is to provide an overview of the current management of the global battery waste stream. We herein present a holistic view of the global battery market and trends, what the key problems are, roadblocks to overcoming these challenges and possible strategies to resolve these issues. The review begins with defining the different battery types, the global market share breakdown by cathode chemistry types, end-use application, geographical localization and economics, followed by the environmental impact of batteries at the EoL. An important aspect of the battery waste management process is the numerous uncertainties and challenges that vary from country to country because of different government factors. Therefore, this paper summarizes the primary challenges around regulations that complicate the smooth transition to a closed-loop lithium ion battery economy that considers the three “R’s,” reduce, reuse, and recycle, principles.

2. Battery Type by Chemistry

Batteries are classified into primary (single-use/disposable e.g., lithium metal, alkaline) and secondary batteries (rechargeable e.g., LIB, LABs, nickel metal hydride (NiMH) etc.). Batteries are further classified by application type i.e., consumer, stationary, and industrial batteries. Commercially, batteries are classified by chemistry type, which includes alkaline, mercury, LABs, nickel-based, and lithium-based batteries. The latter three types of batteries made up 94.8% of the global battery market in 2016 [4].

2.1. Lead Acid Batteries

The LAB was invented by a French physicist Gaston Planté in 1859 and is the oldest rechargeable battery. Despite having a very low energy-to-weight ratio and a low energy-to-volume ratio, its ability to supply high surge currents along with low cost, make it attractive for use in many fields. LAB is a mature technology that is well established and widely adopted. LABs remain as the most preferred and performance-proven backup power solution for most traditional industrial applications. Lead battery life has increased by 30–35% in the last 20 years [31].

The major uses of LABs are as a starter battery, motive power battery, and stationary battery. Automotive batteries for starting, lighting, and ignition (SLI) and traction/stationary batteries (used for standby and emergency power supply) account for approximately 75% and 25% of the total battery lead usage, respectively [40]. Based on the structural differences in the battery plates, LABs are categorized as deep cycle batteries or starter systems. The deep cycle battery includes two distinct subcategories including flooded lead acid (FLA) and valve regulated lead acid (VRLA) batteries with the VRLA type further subdivided into two types, absorbed glass mat (AGM) and gel. According to Grand View Research’s Global Lead Acid Battery Market Analysis in 2020, the LAB market size was valued at US \$58.95 billion in 2019. Among the different lead acid battery types, FLA and VRLA are dominant, with FLA comprising the largest segment. VRLA

held 33.9% market share in 2019 and is estimated to have the highest growth between 2020 and 2027 [1].

2.2. Nickel-Based Batteries

Nickel cadmium (NiCd), nickel iron (NiFe), and nickel metal hydride (NiMH) are the commonly known nickel-based batteries. They are robust battery systems and were invented after LABs. NiCd and NiMH are two similar battery systems, where NiMH has higher capacity and low maintenance compared to NiCd. The NiCd battery was invented in 1899, prior to NiMH, and has been used in portable devices (e.g., video cameras, power tools etc.) for many years because they are effective in maintaining voltage and holding charge when not in use. However, NiCd batteries are also well-known for “memory” effects which degrades the capacity of the battery over time. Due to growing toxicity issues and driven by government regulations imposed by many nations, NiCd batteries are now limited to specialty applications and being replaced by NiMH battery technologies [41]. NiMH batteries do not suffer from the “memory” effect of NiCd batteries. Although there are other Ni-based battery chemistries, they are targeted at select niche markets, hence this review will focus on NiCd and NiMH batteries. Both of these nickel-based batteries fall between LAB and LIB in terms of energy density.

2.3. Lithium-Based Batteries

Lithium metal batteries (LMBs) are nonchargeable primary batteries that have metallic lithium as an anode. Although feasible, a rechargeable (secondary) variant of LMB has not been commercialized on a larger scale. LIBs, which employ a graphite-based anode, were commercialized in the 1990s [42], have high specific energy (~150 Wh/kg), high energy density (~400 Wh/L), long cycle life (>1000 cycles), a broad operating temperature range (charge at -20°C to 60°C , discharge at -40°C to 65°C), and low self-discharge rate (2–8% per month) [43]. LIBs are used in a wide variety of applications [43,44]. The lithium ion polymer battery, a variant of the LIBs, uses a polymer electrolyte instead of a liquid electrolyte for safety and weight-sensitive applications [45]. LIB technology has become the most dominant and fastest-growing battery chemistry in the consumer energy storage market. Advantages of LIBs include long shelf-life, less maintenance, fast charge and discharge, scalability and can be located at or near where the energy is consumed, easy manufacture, and fast deployment [46]. The disadvantage of LIBs includes: requiring protection circuit and disconnect devices to prevent overcharge or thermal runaway, degradation at high temperature and when stored at high voltage, slow charge at freezing temperature, fire risk and transportation restrictions as a result of safety and waste regulations when shipping large quantities [43,44]. LIBs are manufactured in three architectures: cylindrical, prismatic, and pouch cells. Apart from graphite, lithium titanate (LTO) and silicon/carbon are the commonly used alternative anode materials. Commercial LIBs typically use lithium iron phosphate (LFP), nickel cobalt aluminum (NCA), nickel cobalt manganese (NCM), and lithium manganese oxide (LMO) as cathode materials.

3. Battery Market Overview

3.1. Market Share by Chemistry

According to the Technavio Market Analysis in 2020 [47], the 2019 global battery revenue percentage breakdown by different chemistry types is shown in Figure 2. Secondary battery systems account for the majority of the global battery market (73.8%) [2]. Closer examination of the secondary battery sector shows that LABs and LIBs account for 49.94% and 45.74%, respectively, of this market share [47]. It is expected that 81.77% of the rechargeable battery market growth will come from LIBs between 2019 and 2024 [47] because of the growing demand globally.

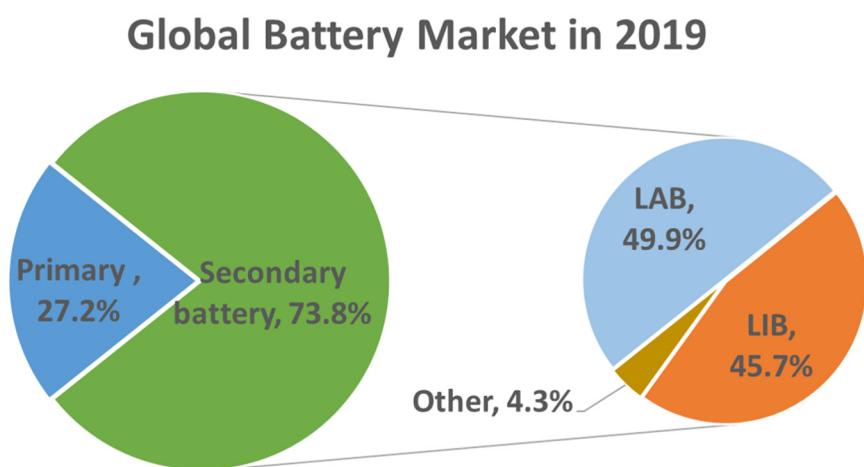


Figure 2. Global battery market share by different types of batteries usage and chemistries in 2019. Data derived from reference [47].

The global battery market is currently segmented into industrial, automotive, and consumer batteries. Based on the market review from 2016 to 2019, there is clearly a shift toward greater use of LIBs (25%), a slight decline in LABs (~10%) and other battery systems which needs to be considered for the recycling of future battery technologies.

3.2. The Global Battery Market Size

3.2.1. Global Battery Industry Growth by Application

The global battery market is expected to grow by 25% per annum to 2.600 GWh in 2030 [7]. The electrification of transportation and deployment of batteries in electricity grids are the main drivers for this global battery demand. Figure 3a shows the global market demand breakdown by applications and the percentage contribution between 2018 and 2030. The demand from electric mobility is expected to see a massive energy growth from 142 to 2333 GWh, where the total market demand from 2018 to 2030 is attributed to EV passenger cars accounting for 60% and commercial vehicles being the rest [7]. As shown in Figure 3b, the demand percentage contribution from consumer electronics (CEs) is expected to have a gradual decrease from 21% to 3% by 2030 becoming marginal in the global battery market in the future, although the demand in capacity nearly doubled. The energy storage capacity demands are expected to grow sharply in the next five years by ten times and then continue to grow at a much slower rate.

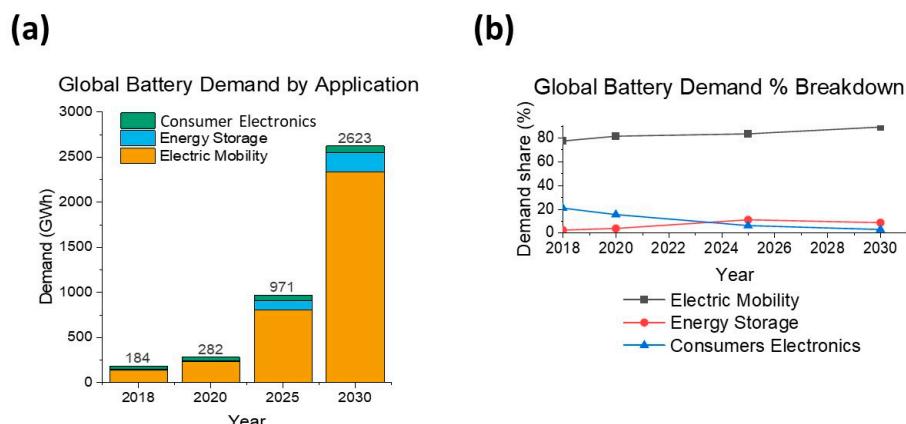


Figure 3. (a) Global battery demand by application from 2018 to 2030. (b) Application demand contributions percentage breakdown from 2018 to 2030. Data derived from reference [7].

The global LAB demand is in the area of vehicle starter batteries, mobile industrial applications, and stationary power storage, including uninterruptable power supply, and off-grid energy storage. The main factors that surge the demand for lead acid batteries are SLI applications in the automotive industry, growth in renewable energy production and high demand for energy storage devices in developing countries [48]. Currently, automotive LABs account for 75% of LAB production and the rest being deep cycle batteries [6]. The telecommunication industry, in countries including, America, UK, India, parts of Africa, Western China, Vietnam, and Brazil, are leading the demand for uninterruptible power supplies (UPS) systems as a power back-up.. This has, in the short-term, resulted in the rapid adoption of LABs as a cost-effective energy storage system [31]. LABs are expected to remain as an integral part of the global battery market for a long time with further growth, although at a significantly slower rate than the lithium ion market. It is estimated that the global LAB market is likely to register a compound annual growth rate of 5.2% from 2018 to 2023 [1].

LIBs have emerged as the most serious contender and alternative to LABs in automotive and energy storage battery sectors. LIBs have been extensively used in energy storage systems (ESSs) and electric vehicles, gradually replacing the large format NiMH batteries [46,49]. Compared to LABs, the LIB technology, in most cases, provide superior reliability and high efficiency. The main disadvantage of LIBs are their high cost, but those costs have plummeted over the past decade and are projected to continue to decrease; while the price of LABs is relatively stagnant. However, each battery technology has an essential role to play in different applications, and the market will ultimately decide which technology best suits a particular need.

It was predicted ESSs and EVs will count for 80% of the \$32 million LIB market in 2020 [7]. Although EVs are not widely used yet, global production rates of LIBs have increased rapidly with a sharp increase in sales of EVs in the past decade [6], as numerous nations are introducing stimulus packages and policies to promote EVs to reduce the impact of greenhouse gas emissions on climate change. EVs are becoming the major driver for LIB production with over 5 million electric cars owned globally by 2019, where over 2.9 million electric vehicles were sold just in the year of 2019, which is an 81% increase from the previous year, and about 20 million are expected to be sold worldwide by 2025 with an average growth rate of 41.7% [6].

3.2.2. Global Battery Industry Growth by Region

The battery market is defined as China, Europe, USA, and the rest of the world (RoW). Global battery demand by region is plotted according to McKinsey analysis as shown in Figure 4a. Geographically, China is the biggest market with 68% of global battery demand in 2018. The current battery capacity demand from China is estimated to increase ten-fold from 2018 levels by 2030. However, with the increase in battery demand in the other major regions and the rest of the world, the percentage share of China is expected to decline to about 43%.

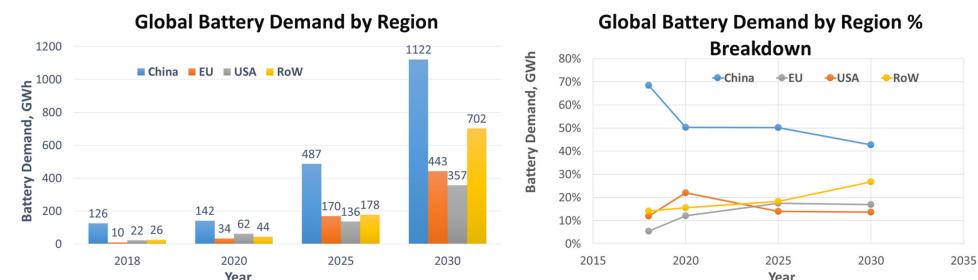


Figure 4. (a) Global battery demand by region from 2018 to 2030. (b) Demand contributions percentage breakdown by region from 2018 to 2030. RoW refers to Rest of the World. Data derived from reference [7].

4. Impacts of Increased Battery Usage

4.1. Impact on Environment

4.1.1. Lead Acid Batteries

Today more than 90% of the world's lead consumption is for the production of LABs [40]. All automotive batteries and 60% of industrial batteries are LABs [4]. LABs contain sulfuric acid and large amounts of metallic lead. The acid is extremely corrosive and also dissolves lead and lead particulate matter. Lead is a highly toxic heavy element that can accumulate in the environment and produce a range of adverse health effects [6]. Exposure to excessive levels of bio-available lead can cause damage to brain and kidney, nerve systems, impaired hearing, and numerous other associated problems [6]. Each automobile manufactured contains about 12 kg of lead from which around 96% lead is used in the LAB, while the remaining 4% are present in other applications [50]. With the continued use of LABs, it is critically important to minimize the contamination of the environment at the EoL by effectively collecting these batteries and recycling materials from these systems that have been established in many countries. While LAB recycling is practiced worldwide and has become a "recycling success story," this is not the case for LIBs.

4.1.2. Lithium-Based Batteries

Unlike lead, lithium is less toxic and historically there has been far less incentive to recycle these batteries. However, as there has been tremendous growth in LIB usage, the mixed metal oxides used in these batteries and significant numbers of LIBs reaching their EoL, waste management is becoming a global issue. LIB products reach EoL after about 3–10 years based on chemistry type and end-use application [1,31,40]. LIBs will be the dominant batteries in our waste streams in the immediate future. The quantity and weight of spent LIBs in 2020 is expected to surpass 25 billion units [42]. In addition to lithium, LIBs contain other metals, such as cobalt, nickel, manganese, aluminum, copper, among which cobalt, nickel, and manganese are considered toxic heavy metals. In particular, the cobalt ions, such as Co^{2+} , are toxic to humans and aquatic life [51]. Global access, sourcing and secure supply chains to these metal materials have also raised concerns about the environmental, economic, and ethical impact in relation to accelerated mining operations, geo-political instability, global quantities of natural metal sources, hazardous working conditions, child labor, and DNA damaging toxicity around the conditions of cobalt mines in the Democratic Republic of Congo [7]. For example, mining of lithium for batteries in Chile has been blamed for depleting local groundwater resources across the Atacama Desert, destroying fragile ecosystems, and converting meadows and lagoons into salt flats [37]. Currently, cobalt is the most expensive element used in LIBs. The current trend in LIB technology development is to move away from chemistries containing high amounts of cobalt, toward towards using LiFePO_4 , nickel-rich NMC and NCA as well as cobalt-free LMNO. These types of batteries minimize the use of cobalt (and other metals) associated with unethical mining and reduces the material cost of LIBs. New chemistries of lithium ion batteries, which aim to eliminate the use of metal oxides and greatly enhance the available energy density, are in development. The two leading chemistries are lithium sulfur [52] and lithium air [53], which have 5 times and 10 times the energy density of commercial lithium ion batteries.

LIBs typically use a liquid or gel (used in lithium ion polymer batteries) electrolyte. The most common electrolytes contain lithium hexafluorophosphate (LiPF_6) salt as the most suitable lithium salt, but it is known for causing systemic toxicity, respiratory failure, cardiac arrest, and death even with little physical contact with the compound (oral ingestion LD₅₀ value of LiPF_6 has been established to be within the range of 50–300 mg/kg body weight) [54]. LiPF_6 also reacts readily with mucous tissues and is reactive to water to liberate dangerous hydrofluoric acid [55,56] under the concomitant formation of very toxic phosphorus degradation products. Furthermore, the LiPF_6 is typically

dissolved in organic carbonate solvents which are flammable and toxic. Therefore, safe recovery or containment of the electrolyte system will be required at EoL.

4.1.3. Nickel-Based Batteries

NiCd and NiMH batteries are the two major types of batteries in most countries current battery waste stream. Cadmium can cause lung cancer and kidney damage. Similar to mercury batteries, which have been banned already, the elimination of cadmium-containing batteries is being closely considered in some countries. For instance, the NiCd battery has been banned and substituted by NiMH batteries in Europe [57] and are mounting concerns that LABs may also be targeted by restrictive legislation [58]. Unsurprisingly, NiCd global sales have decreased by 6% per annum while NiMH sales have increased by 5% per annum between 2002 and 2012 [59]. Although NiCd is no longer used for small portable devices, they are still used for emergency lighting units. The industrial use of NiCd batteries is mainly due to their very long lifespan of up to 20 years and reliability in either cycling or standby application [59]. Small NiMHs are used in home appliances such as toys, and large NiMH are used in hybrid vehicles, where low maintenance is advantageous [59]. According to McManus's studies on the environmental consequences of the use of the different types of battery chemistries, NiMH and LIBs are the most energy intensive batteries to produce [60]. Recently Mahmud et al. [61] compared the environmental impact of LIBs and NiMH batteries over the whole life-cycle by considering the global warming, eutrophication, freshwater aquatic ecotoxicity, human toxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity. The results revealed that there is a significant environmental impact caused by NiMH batteries compared to LIBs, largely due to the use of relatively large amounts of toxic chemicals in their production. The extraction, crushing, refining, and processing of Cd into compounds for NiCd batteries and thin film photovoltaic modules also pose risks to groundwater, food contamination, and workers that are exposed to these hazardous chemicals [37].

5. A Circular Economy Proposed for Battery Value Chain

The Circular Economy is an economic system aimed at eliminating waste and the continual use of resources rather than sourcing new materials under the current Linear Economy. The Circular Economy model not only employs waste management but considers reduce, reuse, recycle, and responsible manufacturing, which could support the development of new industries and jobs, reducing emissions and increasing the efficiency of using natural resources [62]. The Circular Economy concept has attracted significant interests to both scholars and practitioners as it is an operationalization process to achieve sustainable development globally [63–65].

According to the world economic forum insight report [7], a circular battery value chain is one of the major near term drivers to achieve the 2 °C Paris Agreement goal in the transport and power sectors. A closed-loop battery value chain could enable 30% of the required reductions in carbon emissions in the transport and power sectors. Figure 5 demonstrates the vital components of the circular battery value chain, where V1G refers to smart charging. Battery repair and refurbishment, repurposing of end-of-life batteries, and battery recycling are identified as some of the critical steps to address the key challenges in the battery value chain, especially as the massive expansion of raw material demand and supply is predicted, where the demand of lithium and nickel are forecasted to grow by a factor of 6 and 24 by 2030, respectively [7]. According to the report in 2019 from the International Renewable Energy Agency (IRENA), the V2G (refers to vehicle to grid) solutions could lower the costs for electric vehicle charging infrastructure by up to 90% and could cover 65% of the demand for battery storage power globally [7].

Refurbishment and repair of battery systems used in EVs and energy storage systems (ESS) could extend their lifetime, reducing the demand for new capacity and improving costs over the lifetime. During refurbishment and repair, degraded or faulty battery modules are exchanged to enable the capacity of the remaining modules to be used further

in an EV or alternative application. However, it is assumed that the refurbishment will be limited in the long term to only 5% of EoL EV and ESS batteries because the trend of homogenous battery ageing undermines the business case for exchanging deteriorated modules [7]. Furthermore, due to the lack of incentives for automotive companies to optimize battery design for repair and refurbishment where different system designs, it largely depends on the manufacturer's will to make repurposing (second-life) or recycling even less complex [7].

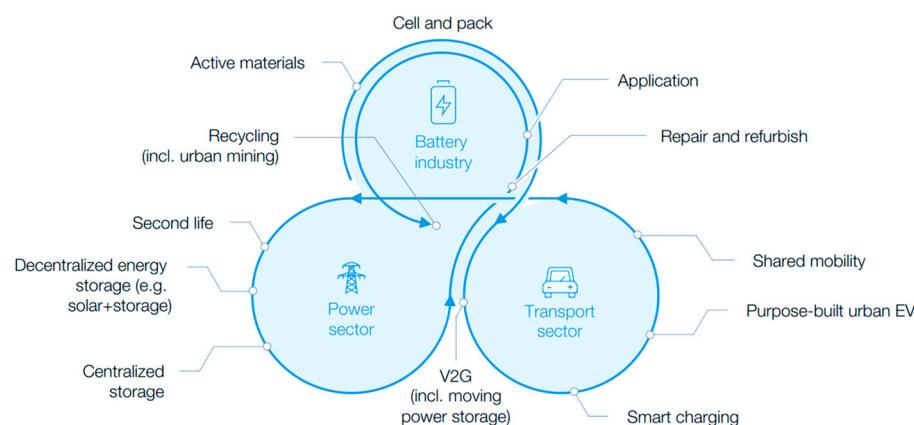
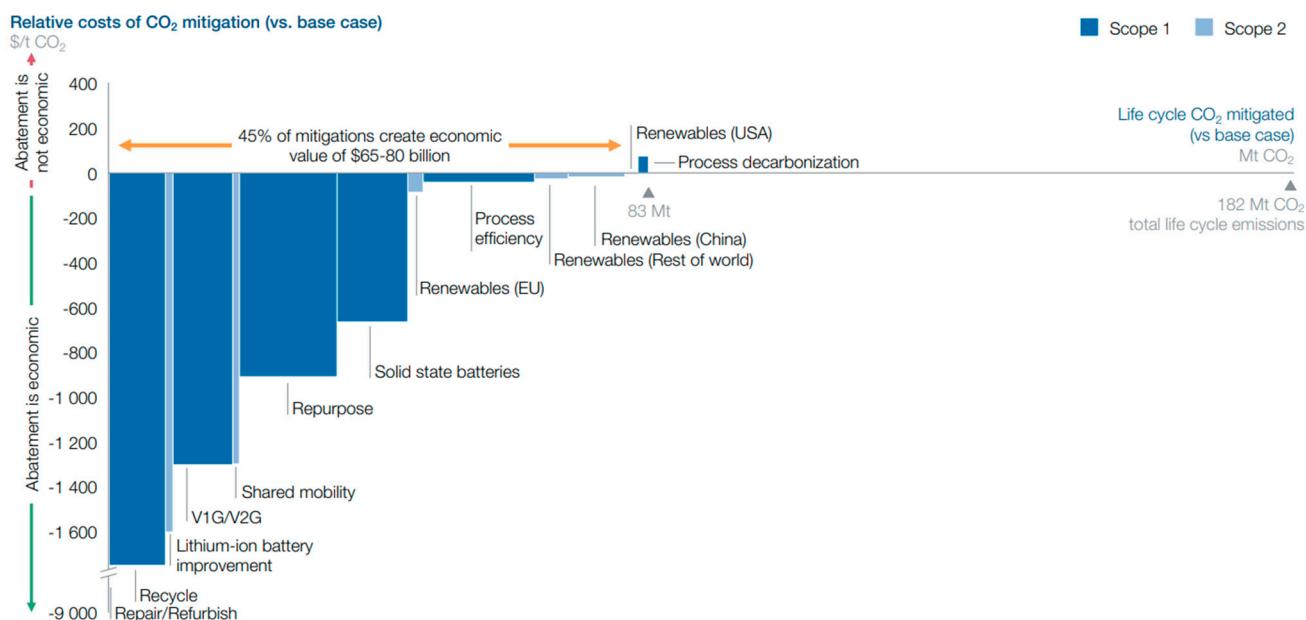


Figure 5. Circular value chain illustrating the coupling of transport and power sectors. V2G refers to vehicle to grid. Figure from reference [7].

The impact and cost of the improvement in each of the key areas in the closed-loop battery value chain as a function of the carbon abatement cost is visualized in Figure 6 [7]. The negative cost means that circularity and innovation provide solutions that have a better cost performance compared to its base case alternatives. Combining the analyzed levers, the greenhouse gas emission can be reduced from 182 Mt to around 100 Mt at a negative cost.

CO₂ abatement curve shows economic potential of levers to reduce battery value chain emissions



Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

Figure 6. Circular Economy and innovation lever impact on life cycle green house gas (GHG) intensity of battery production in 2030 [7].

6. Status of Battery Recycling

6.1. Battery Waste Recycling

Battery waste is part of the wide range of e-waste and many current battery recyclers are also e-waste recyclers [66]. The EoL batteries, in particular those from small consumer electronic products, are traditionally disposed of, usually in landfills or incinerated to obtain valuable metal components. However, these practices are considered not eco-friendly. Battery waste is an essential source for recovering crucial valuable metals, including lead, lithium, nickel, cadmium, and copper. The global growth in mineral demand is illustrated in Figure 7. The recovery of battery metals from the EoL batteries will reduce the burden on landfills and environmental and human health concerns. Ultimately, the concept of battery recycling has gained prominence because of its well documented economic and environmental benefits.

Growth in Minerals Required for Batteries

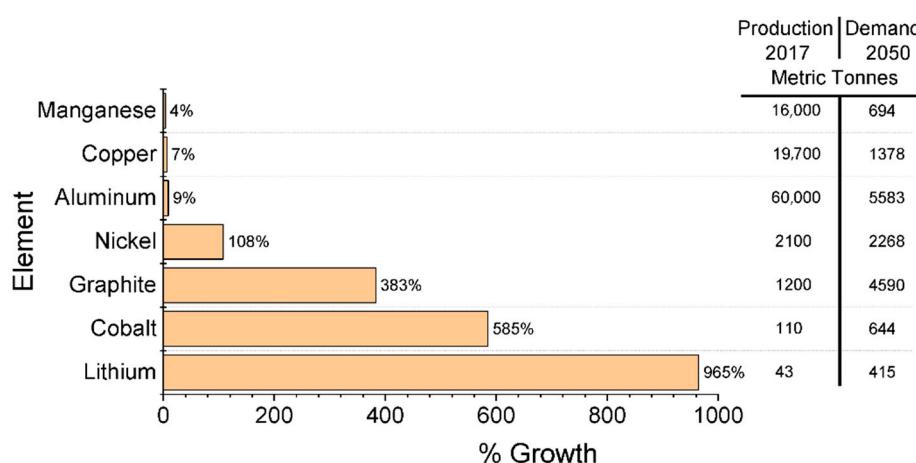


Figure 7. Demand growth in minerals 2017 data from reference to 2050. Based on reference [37].

6.2. Lead-Acid Battery Recycling

In 2018, LAB recycling accounted for 86.14% of global secondary battery recycling share [67] and is estimated to lead the battery recycling market in terms of value from 2020 to 2025 [68]. Recycling of LABs is one of the great success stories for the recycling industry with up to 99% of the battery able to be recycled [6] because of the product design and chemical properties, the lead-based products are easily identifiable, economic to collect and recycle. Lead has the highest EoL recycling rate of all commonly used metals [40]. In developed economies, such as Europe and North America, the used lead batteries are managed very well via efficient point of sale return systems, transported and recycled by highly regulated operations that have high standards for worker safety and operational practices [6,7]. These high recycling rates, coupled with the fact that LABs are manufactured from recycled material, make them a great example of a functioning battery Circular Economy. However, in many other developing regions, up to 50% of EoL lead batteries are recycled in informal or below standard facilities that has resulted in substantial releases of lead into the environment and high level of lead exposure to society. China, a leader in LAB production, has taken action to protect the environment by introducing strict guidelines that have begun to eliminate substandard operations [50]. The pyrometallurgical process is dominant in the LAB recycling process. There are still a number of drawbacks of the pyrometallurgical lead recycling process, primarily due to operational and environmental concerns [69]. A typical process flow diagram is shown in Figure 8. High purity lead can be recovered both from pyrometallurgical and hydrometallurgical processes. Because of increasing energy costs of pyrometallurgical lead recovery and catastrophic health implications of lead exposure from increased lead particulate air emissions, there is growing interest in developing novel processes to recover lead from EoL LABs [6]. Some innovative

techniques such as citric acid calcination, atomic economic method, membrane direct electrolysis, and electrokinetic separation have been studied in the past few years, which demonstrated significant economic advantages over the traditional recycling method as well as reducing secondary pollution [69]. The calcination technique makes the recovery of lead more self-sustained, and the electrowinning technique reduced recycling process steps [70].

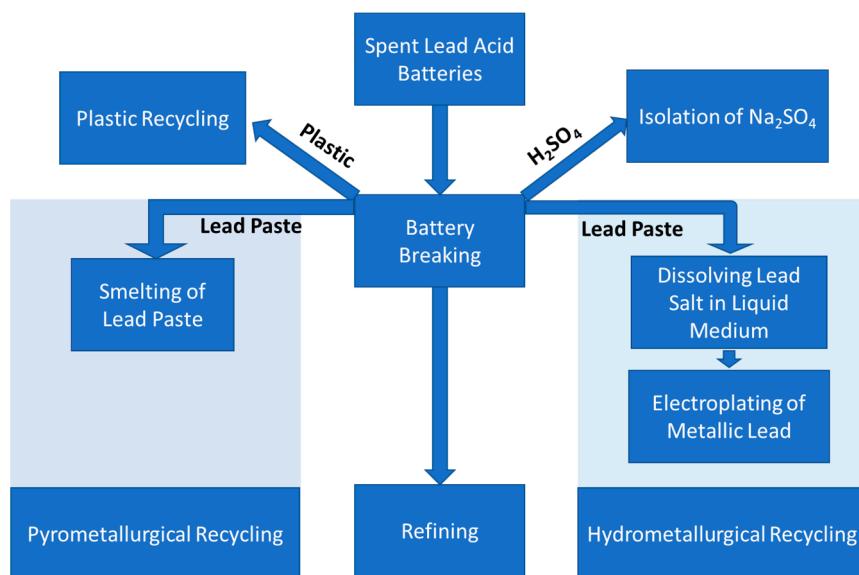


Figure 8. Lead acid battery pyrometallurgical and hydrometallurgical recycling process flow diagram plotted based on reference [6].

6.3. Nickel Metal Hydride Battery Recycling

The nickel-based battery industry contributes to less than 5% of the secondary battery recycling market share [67] and have been recycled commercially for many years [25]. Not all of the materials are being recovered as high value products in this recycling process. The nickel and iron are recovered by rotary hearth and electric-arc furnaces as ferronickel to feed stainless-steel production. As this is a high-value product with a huge market, there is no need to separate the nickel from the iron. However, using this technique loses the rare earths in the metal hydride to the slag, which is used as roadbed aggregate in place of gravel. A typical NiMH battery contains around 7% of rare earth elements including Ce, La, Nd, and Pr [25,71]. The pyrometallurgical process has been found useful in extracting metal elements with relatively high concentrations while the hydrometallurgical process is more effective to recover elements found in much lower quantities. Over recent decades, there has been an increasing demand for rare earth elements for use in batteries, motors, wind turbines, electronic consumer goods, and nanotechnology [71] along with China's policy change in rare earth import restrictions, have provided an unexpected incentive to countries to recover rare earth elements at EoL. In 2011, Umicore and Rhodia announced the first recycling program for rare earth metals from NiMH batteries [71]. Honda also started its recycling program in 2013 to extract 80% of rare earth elements from used hybrid batteries with 99% purity that is similar to mined rare earths [72]. Although Cd is not present in NiMH battery waste because of mislabeling of batteries [73]. The mislabeling along with lack of labelling standards for different battery chemistry types is a critical issue in waste battery recycling. The mix of undesired battery types not only results in feedstock contamination and process complexity, but also increase fire risk which will be discussed in LIB recycling section. A brief process flowchart of NiMH battery recycling via the hydrometallurgical process is visualized in Figure 9 [74]. In this process concentrated sulfuric acid is used to leach metal ions from the waste scraps. From this process, Ni, Co, Zn, Fe, Al, Mn, and Cd are recovered. A bio-hydrometallurgical process is another

technique used to recover nickel in high purity, but the rate of bioleaching is very low and the extent of nickel and iron extracted are less than 50% which has restricted industrial uptake [75]. NiMH battery recycling yields achieve the highest return in nickel and with ample demand from other material supply chains making it profitable [35], whereas low demand for cadmium materials has reduced the profitability for recycling NiCd batteries.

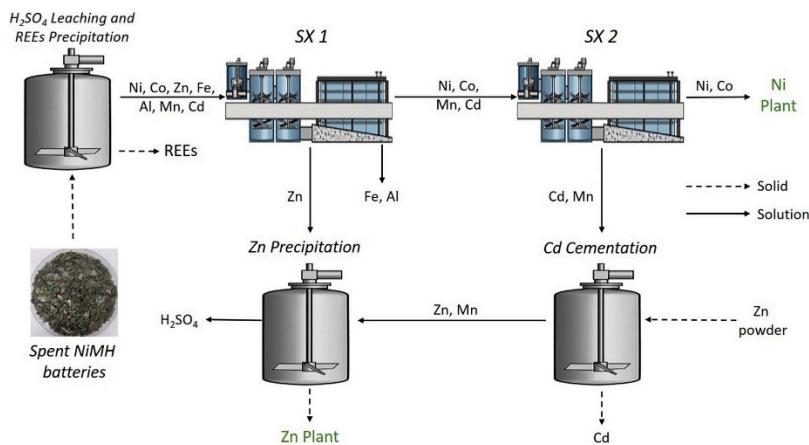


Figure 9. Nickel metal hydride battery recycling process flow diagram [74].

6.4. Lithium Ion Battery Recycling

6.4.1. Why LIB Recycling?

Compared to LABs, NiCd, and mercury batteries, the LIBs are technically considered “green,” since they, as discussed in the environmental impact section, have far lower content of toxic metals [36]. The widespread adoption of LIB technology and a recent sharp increase in LIB demand in consumer electronics (CE) and EVs has, however, lead to environmental and increased financial concerns (valuable battery elements). In particular, cobalt production is concentrated in the Democratic Republic of Congo, which makes it unpredictable and highly susceptible to political risks [76]. Thus, there is growing interest in many countries to implement LIB recycling in recent years.

6.4.2. Economic Challenges of LIB Recycling

In 2020, Merlin et al. indicated about 80% of LIBs that are reaching their EoL originate from portable electronics [29]. However, LIB recycling has not seen large-scale uptake globally primarily due to economic barriers. As a result, there are two opposing opinions regarding the future challenges of LIBs at EoL. On the one hand, LIB recycling is regarded as less attractive because of the complexity of the battery design, complexity of battery material chemistries and current lack of sufficient waste stock to supply the LIB recycling industry for the process to be economically viable [35]. Currently, it is believed that the LIB recycling process needs subsidies given the current market conditions [35]. On the other hand, it is claimed that the recycling of lithium batteries is profitable and convenient given the recent EV boom and project growth of EVs [24,34]. It is estimated that the total value that can be recovered from NMC batteries is over US \$7000/ton of battery waste based on the current metal resource pricing and assuming 90% recovery efficacy [24].

The lack of lithium battery recycling in Europe was claimed to be due to low volume streams of EoL LIBs. In 2019 there was only 5% of LIB battery waste collected for recycling including car batteries [31,77,78]. According to the Consortium for Battery Innovation the volume of lithium battery production is relatively low in North America and therefore the materials recovered from LIB recycling processes would likely have to be exported to other countries, such as China [31]. Although the manufacturing rate is relatively high, spent LIBs in mainland China have the same fate as NiCd and NiMH batteries for which no proper disposal and collection schemes are in place. The spent LIBs either end up in landfill along with other solid waste or stockpiled in warehouses without proper handling [66].

South Korea as one of the major LIB recycling regions reported collection of the EoL LIBs, and an extended producer responsibility (EPR) policy was adopted for battery recycling in 2003 [79]. Wang et al. [32] analyzed the economics of LIB recycling infrastructure and concluded a well-functioning collection and recycling infrastructure is critical to minimize associated environmental impacts and recycling can only be economically viable if sufficient amounts of spent LIBs were generated. According to Zeng et al. [33], the EoL CEs and EVs often enter a small second-hand market, since most consumers prefer new batteries leading to fewer stakeholders in the spent LIB market than in the general e-waste market, providing more opportunities for spent LIB recycling. The 5% statistic value of LIB waste collected is misleading, argued by several companies. LIBs could be recycled at a high rate like LABs, but the issue has simply not yet been viewed as one of critical importance [31]. LIB recycling will likely become of significant importance once large amounts of EVs, ECs, and industrial LIBs reach to their EoL and flow into the e-waste stream. It was reported that due to higher buying prices for waste materials, the waste batteries generated in Europe and North America have been exported to China [80]. Asia dominates the global LIB production driven by China which accounts for 45% share of production, followed by Japan (19%), Europe (15–18%), and Korea (7%) [81]. A survey of ~50 global LIB recycling companies found about 100,000 tons of LIBs were recycled globally in 2018, of which 67,000 tons were recycled in China and another 18,000 tons in South Korea [29,82]. The 100,000 tons of waste LIBs represents about 50% of what reached EoL in those jurisdictions [30]. Globally, Globally LIB recycling is small scalescaleaccording to an Australia-based market research company Technavio, where global LiB recycling only contributed to 8.86% of the secondary battery recycling market share in 2018 [67]. China and Korea pay a much higher price for waste LIBs than other businesses in Europe and the US because they achieve higher recycling efficiencies, which make them the preferred destinations for LIBs. Some recyclers in the US, Europe, Canada, and Japan have efficient process technologies to recycle LIBs, but unfortunately do not have the waste battery supplies to make it profitable [30]. Without government regulation to help keep the waste locally, competitive price-based wastepurchase and development of economic recycling processes, the LIB or EV battery recyclers in America and Europe, despite having efficient processes will struggle to acquire the volumes of waste batteries required for profitable operations [29]. According to the Circular Energy Storage's newest data, more than 1.2 million tons of waste LIBs will be recycled worldwide by 2030; by then the amount of recycled lithium available to the global battery supply chain will be equivalent to about half of today's lithium mining market, while the amount of recycled cobalt in 2030 will be around a quarter of today's equivalent [82]. The global EV battery reuse and recycling market generated \$61.5 million in 2018 and is estimated to reach \$7,809 million by 2025 with a CAGR of 99.8% [80]. Battery collection network and recycling infrastructure will need to be promoted and further developed by government policies. Regulations and policies will be discussed in the later section.

Co, Li, and Ni are critical metals of high value in LIBs. A typical NMC LIB comprises about 7% Co, 7% Li, 4% Ni, 5% Mn, 10% Cu, 15% Al, 16% graphite, and 36% other materials, where lithium is expressed as lithium carbonate equivalent ($1\text{ g Li} = 5.17\text{ g LCE}$) [83]. The composition range of LIBs is summarized in Table 1, while the historical price trends of these elements are summarized in Figure 10. Most of the current LIB recycling processes and research is focused on the recovery of high value elements such as Co, Ni, and Li to a high purity level that allows for their reuse in battery manufacturing. However, the price of cobalt has fallen dramatically in the past few years as shown in Figure 10a. In the same period, the lithium price also dropped from its peak in 2018 by 51% and the price is predicted to slide despite forecast supply disruptions and strong demand growth in the future due to “excess” supply [84]. If the cobalt price continues to drop, the recovery of cobalt from spent LIBs would struggle to compete with the mined cobalt in price. Depending on the purity and prices, if battery manufacturers chose mined over recycled, it will force many recyclers out of business. “Lithium supply is growing far

quicker than lithium demand and this can be said for all battery materials as the EV pick up rate is not expected to really start increasing until the early to mid-2020s," said Marcel Goldenberg, manager for metals and derivatives at S&P Global Platts [76]. The oversupply of mined lithium products was mainly caused by the commissioning of lithium mineral operations in Australia outpacing mineral conversion capacity in China, which has been a significant contributor to the falling lithium prices since quarter one of 2018 [76]. The commissioning of four lithium mineral projects in Australia and Brazil, coupled with the ramp-up of production at several existing brine and mineral operations was responsible for the increase in capacity [84].

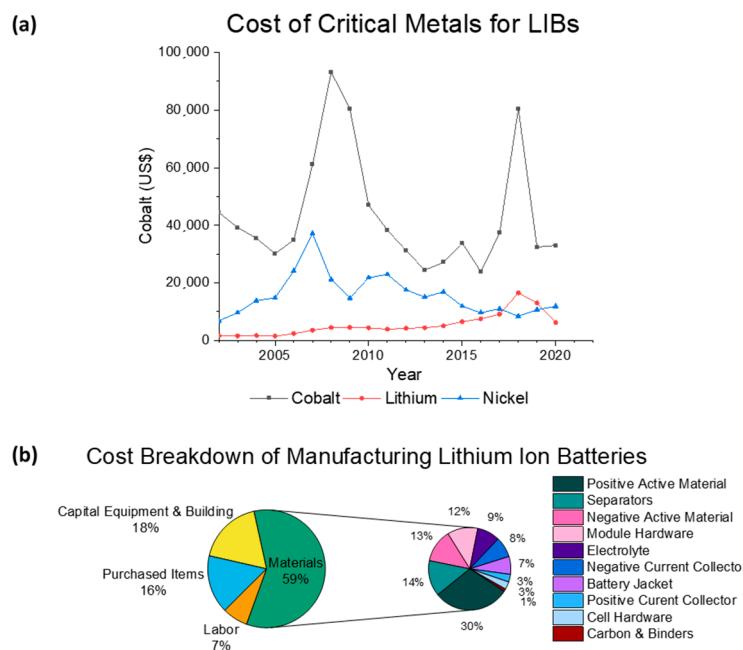


Figure 10. (a) Historical price of cobalt, nickel, and lithium between 2002 and 2020. Data from [85,86]. (b) Cost breakdown by percentage for making lithium ion batteries. Plotted based on reference [87].

Table 1. Component range of typical LIBs and current commodity value of each metal element in 2020.

Component	Composition ^a %	Commodity Value ^b US\$/tonne
Cobalt	5~20	33000
Nickel	5~15	11846
Lithium	1~7	6170
Manganese	10~15	47
Iron	5~25	87
Aluminium	4~24	1611
Copper	5~10	5183

^a Data from reference [33]; ^b <https://tradingeconomics.com/commodities>, accessed on 6 May 2020.

Cobalt, among the other metals present in common cathode formulations, accounts for up to 60% of the cathode cost [81]. The overall cathode material formulation alone counts for 30% of the battery material cost [87]. The cost breakdown for LIBs is shown in Figure 10b. In order to reduce the battery raw material cost, batteries comprising of NCA cathodes with much less cobalt (cf. NMC) and cobalt-free LFP batteries have become more preferable in the LIB market. In particular, LFP is very popular in China which is

the biggest market for EVs [23]. Recently, Chinese battery manufacturers such as CATL and BYD, have increased their nickel to cobalt ratio in battery cathode materials to 10:1. Figure 11 shows the market demand for different LIB chemistry in 2018. NMC, NCA, and LFP are the top three chemistry types. The share of NMC is expected to increase up to 48% in the LIB global production by 2025 from 19% in 2018 according to Frost and Sullivan [81]. It is also forecasted by Goldman Sachs Global investment research that nickel-rich cathodes such as NMC and NCA will be in high demand because of the higher energy densities that can be achieved with these mixed metal oxides and will be the mainstream chemistry to gain market share against LFP batteries [24]. The metallic component of NCA and NMC are summarized in Figure 11. For most of the cathode chemistries containing Co and Ni, the recovery makes economic sense. But for cathode materials, such as LFP and lithium manganese oxide (LMO), the constituent metal value is very low according to the metal price listed in Table 1. Another point to consider from the current trend of using cheaper metals for LIB manufacture is that it will make the LIB industrial recycling less profitable in the future under current processing and business models [25]. Except for the above mentioned chemistry shift, another long-term financial concern for the recycling industry are the challenges associated with emerging energy technologies, such as lithium air, or a different vehicle propulsion system, like hydrogen-powered fuel cells. These developments could diminish the growth and impact of the projected EV market in the near future and therefore sustainability of recycling LIBs [27]. For example, in Q4 2017 when the Japanese government and automakers started to promote hydrogen fuel cell vehicles a drop in EV sale from 2018 was observed [80]. However, the current hydrogen fuel cell technology has several barriers to overcome before it can compete with EVs, including high cost and safety issues (hydrogen gas), building hydrogen infrastructure and therefore, companies are still actively investing in R&D to develop alternative low-cost fuel cells [47]. The impact of low cobalt LIBs and possible solutions was discussed by Gaines recently [26] where the profitability of recycling low cobalt content LIBs will depend on the advancement of recycling technology, rely on subsidies and/or government regulations [26].

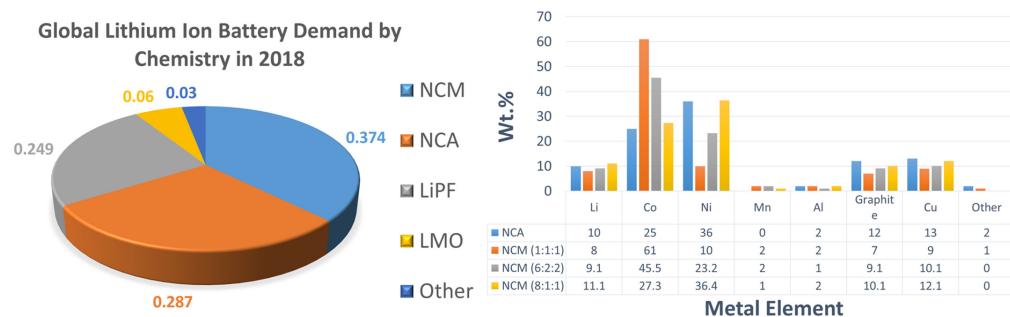


Figure 11. (a) Global lithium ion battery market share by chemistry. (b) The material composition weight percentage breakdown of nickel cobalt aluminum (NCA) and nickel cobalt manganese (NCM) lithium ion batteries. Plotted based on data from reference [81].

6.4.3. Battery Recycling Policy Status

Currently, there are no specific recycling regulations implemented in the main markets, including China, EU, and the USA, where waste battery management varies significantly. Zhang et al. [39] reviewed spent battery management regulations in the major battery markets, such as EU, Japan, and China and recycling strategies of EoL LIBs. They concluded a complete waste battery collection system should be established; promote the extended producer responsibility (EPR) and encourage consumers to send waste batteries to a designated battery collection points; and the management practice should be continually evaluated and strengthened in order to deal with the emergence of new LIBs chemistries because of the rapid technology advancement. Zeng et al. [33] did a critical review on the LIB recycling problem in China recommending the EPR concept and suggested regulation

is needed to curb illegal trafficking and unlicensed recycling of e-waste. The following section summarizes the regulation and policies in regard to LIB waste in the major regions.

- Europe

The EU legislation Directive 2000/53/EC of the European Parliament and of the Council of September 2000 on EoL vehicles require that EoL vehicles should be designed in a way that they can be easily recovered, reused, and recycled. In addition, the directive also requires the free delivery of EoL vehicles to authorized treatment facilities and prohibits landfill and incineration of these batteries [88]. The recycling of LIBs is also encouraged by legislation in the EU where the Battery Directive 2006/66/EC was instituted. The directive requires each EU Member State must meet a collection rate of 45% and a recycling efficiency of at least 50 wt% for non-lead acid and non-nickel cadmium batteries [89,90]. The EU Battery Directive regulations also require battery producers to take responsibility for their waste at EoL. The producers have to pay for the collection, treatment, recycling, and disposal of waste batteries in proportion to their market share [7]. The UK waste batteries and accumulators regulation came into force in 2015 which requires appliances to be designed in such a way that the batteries may be easily removed [91]. The compliance scheme will also register producers with an appropriate environment agency to track waste batteries and reinforce recycling [7]. In Germany, regulations require all parties along the battery value chain to take corresponding responsibilities to recycle batteries. In particular, GRS Battery Foundation (Germany), was established as the common collection scheme for battery recycling under the German Battery Act. The GRS battery foundation was formed and supported by German battery producers and the electrical and electronics industry association (ZVEI) [24].

- The United States of America

In the USA, some not for profit organizations and industry associations are playing an essential role in battery recycling [24]. Rechargeable Battery Recycling Corporation (RBRC), a not for profit organization, promotes recycling of rechargeable batteries through the networks of corporations, public sector, retail customers, and communities. The not for profit trade battery industry group Portable Rechargeable Battery Association (PRBA) is another key participant in battery reuse and recycling in the US, promoting both a recycling business and related regulations. PRBA was formed by companies Energizer (USA), Panasonic Battery Corporation (Japan), SAFT America (USA), Sanyo Energy Corporation (Japan) and Varta Batteries (Germany) [92]. PRBA members established pilot battery recycling programs in New Jersey, Minnesota and Vermont. Battery recycling services are provided by PRBA through its member companies including Umicore, Call2Recycle®, Battery Solutions, KBI and Retriev Technologies [92]. PRBA has also specifically developed a public education and battery recycling program, named Call2Recycle® Program, to be implemented nationally [92]. There are no LIB waste management laws at the federal level in the US. However, Environmental Protection Agency (EPA) classified other types of battery waste, including LABs and NiCd, as hazardous waste. LIBs can only be categorized and regulated as hazardous waste at the federal level if they fail the ignitability, corrosivity, reactivity, and toxicity tests developed by the EPA. At present, LIBs are not regarded as hazardous waste in the US federal level although a few studies were done in the past few years to assess whether they should be classified hazardous waste in the past few years [93]. At present, there are nine states that are regulating the EPR program for rechargeable batteries [80]. Both the 2006 Californian and the 2010 New York rechargeable battery recycling Acts banned landfill disposal of household batteries. The Californian Act classified LIBs as hazardous because of the excessive levels of Co, Cu, and Ni metal species and requires that retailers must have a system to accept and collect used rechargeable batteries for reuse, recycling or proper disposal including the take back at no cost to the customer [94]. Under the Acts, battery manufacturers are also required to arrange the return of the used batteries and recycle them at their own expense [95]. In New York LIB

products have to be labelled appropriately to facilitate the sorting step at the front end when used batteries enter the recycling process [39].

- Asia Pacific region

In Australia, the development of policy and regulation frameworks in regards to deriving resource recovery from battery waste is relatively immature or non-existent compared to international counterparts [93,96]. The Australian Product Stewardship Act was established in 2011 which acknowledged the shared responsibility for managing wastes and their impact throughout the life cycle of a product. However, battery waste, photovoltaic cells, and e-waste from other sources are not currently included in the National Television and Computer Recycling Scheme (NTCRS) but have been recognized as priority areas for waste management in Australia during 2020–2021 [97]. To date, the Australian Capital Territory was the first to ban e-waste landfill and made its recycling mandatory in 2005, South Australia and Victoria followed by introducing landfill bans in 2010 and 2019, respectively [98–100]. Some organizations and retail stores, such as Australian Battery Recycling Initiative (ABRI), Mobilemuster, Aldi and Officeworks, offer a battery collection service for recycling. A sophisticated LIB recycling industry does not exist in Australia, and the collected LIBs are typically sent overseas for processing [101,102]. As Australia is one of the major global lithium producers, it was recommended by Prio et al. to establish a lithium leasing system, known as servicing to encourage the development of better governance practices and healthy recycling infrastructure for lithium [103]. In Australia, the battery National Stewardship Scheme was established in 2020 which requires battery manufacturers and importers to pay a fee for EoL processing per battery.

By contrast in Japan, battery makers commenced recycling batteries via retail dealers from as early as 1994 [24]. From 2000 onwards the Japanese government provided subsidies and required battery makers to recycle NiMH and LIBs. In 2001, a law for the promotion of efficient utilization of resource came into effect focusing on recovery and reuse of small rechargeable batteries including LIBs. The law on the promotion of reuse and recycling of used small electronic equipment was put into effect in 2013, which outlined the roles and responsibility of manufacturers, retailers, consumers, processing enterprises, and the government in this process [104]. The Japanese battery makers established recycling companies to deal with battery waste. For example, Nissan and Sumitomo formed 4R Energy to recycle batteries. On top of this, Japanese unions are also promoting the recycling industry [24].

Supportive recycling policies in China are on the rise. On the national level, energy saving and the new energy automotive industry development plan was announced in 2012 for battery makers to strengthen the recycling of used batteries and encourage the development of specialized recycling companies [105]. In 2015, both battery pack and EV makers were encouraged to carry out the recycling research plan according to the automotive battery industry standard conditions. An explicit extension of the producer responsibility system was adopted in China in early 2016 through the implementation of policies including EV battery recycling techniques and standard conditions of comprehensive utilization of waste EV batteries [24] including reuse of retired EV batteries in other applications such as energy storage. Incentives and subsidies for battery recycling, in particular EV batteries, and their reuse have been implemented in China, such as; (1) The “No Waste City”, which was announced in 2019 to set up a “green supply chain” comprising recycling companies, large corporations, retailers, and support from government departments. The aims include recycling and reuse of LABs and LIBs [106]. (2) The Ministry of Industry and Information Technology has required car manufacturers to allow the public to repair, drop, or exchange their old batteries [80]. As of 2018, EV manufacturers were required to use unique IDs to trace their batteries to ease the second life and recycling industries [80]. (3) Non-government electronic product recycling platforms are also emerging at Suhuishou, Aihuishou, and Huishoubao [107]. Which has led to over 100 enterprises in China being created that have the relevant qualifications to dismantle e-waste, including LIBs [24,108].

The main barriers for recycling of LIBs from the EV stream in China include insufficient collection procedures, improper dismantling, illegal dismantlers, and insufficient government supervision [109]. The LIB recycling issues raised in China, one of the major LIBs market, are also similar problems common in other global regions, which was noted in a recent whitepaper by CSIRO on the status of LIB recycling Australia [28].

6.4.4. Recycling Process Challenges

The development of technology for resource recovery from LIB waste has mostly been driven by policies and regulations that ban landfill disposal, set resource recovery targets, and provide incentives (or penalties) to manufacturers and distributors [28]. Compared to LAB and NiMH, LIBs are compact, come in a variety of sizes and shapes, not designed to be disassembled and have many different components and chemistries which add to the difficulty of its recycling. Furthermore, dismantling systems adds labor costs for LIB recycling. All of the above-mentioned factors lead to the complexity of the recycling of LIBs.

Gaines [25] reviewed the recycling technologies for LABs, NiMH, and LIBs to find that the lack of collection of LIBs resulted in some LIBs being mixed into the LAB waste stream presenting an explosion risk to LAB recycling plants. To meet the specifications of manufactures buying the recycled materials, recyclers need to sort and separate batteries by chemical composition [27]. One of the challenges in sorting spent LIBs is the difficulty of identifying the chemistry inside the battery because of the lack of proper labelling, standard design, or clear signage on the pack, which makes it hard to automate the sorting process with robots [110]. Ideally, if LIBs have a or so-called battery passport, it would make the sorting and tracking of battery waste much easier. Harper et al. [110] recently reviewed the recycling of LIBs and discussed the possibility of using blockchain, artificial intelligence (AI), and robotic technology in tracking batteries, thereby reducing fire and health risks to the labor force in the recycling process. From the discussion, Harper et al. [110] concluded that it is possible to use blockchain technology to provide full life cycle tracking of battery materials and China has signaled its intention to use this approach in the future. Interestingly, battery tracking is also of great interest and strong interest has been seen from the SLBs community (discussed later).

Normally if the batteries do not need to be disassembled, for example, the small LIBs in CEs, crushing and screening is considered easier than manual dismantling [111]. For large LIBs, such as EV batteries, the recycling process typically starts with discharging the spent batteries, then disassembly down to the module or cell level. The automation process involved in dismantling EV batteries presents major challenges [110]. In the manufacturing sector robotics and automation are performed in highly structured facilities, where robots make preprogrammed repetitive actions with respect to exactly known objects in fixed positions. In the recycling cases, the robotic system to be developed need the ability to handle a variety of objects of uncertain dimensions. Not to mention there is no standardization of design for LIB packs, modules or cells within the automotive sector and it is unlikely to happen in the near future [110]. As a result of these current limitations, AI research offers a possible solution to this major challenge. There is some progress towards the automated sorting of consumer batteries, such as the Optisort system [112]. However, it is currently limited to small cylindrical batteries and a large amount of pre-sorting by hand is still needed prior to entering the Optisort machine [112]. As the recycling of large EV batteries is very expensive under the current recycling methods and not very profitable [80], reuse of EV batteries is considered an attractive option for automobile and battery makers. It was reported that recycling companies can make up only a third to half of the recovery costs by selling recycled critical materials [80]. The next section will discuss the main battery recycling technologies and technical challenges. The battery reuse will be discussed in a later section.

Pyrometallurgical and hydrometallurgical, as well as other techniques including direct process, biometallurgical, and electrochemical processes have been employed for LIB recycling. Newer processing technologies, process design, and modelling for LIB

recycling were discussed by Gaines [113], where the report shows that there are great improvements in the material separation in the recycling design as well as in-process modelling, however, of the several recycling methods reviewed none is ideal with each method having its own advantages and drawbacks. Spent LIB recovery is well illustrated by Xiao et al. [114] as shown in Figure 12.

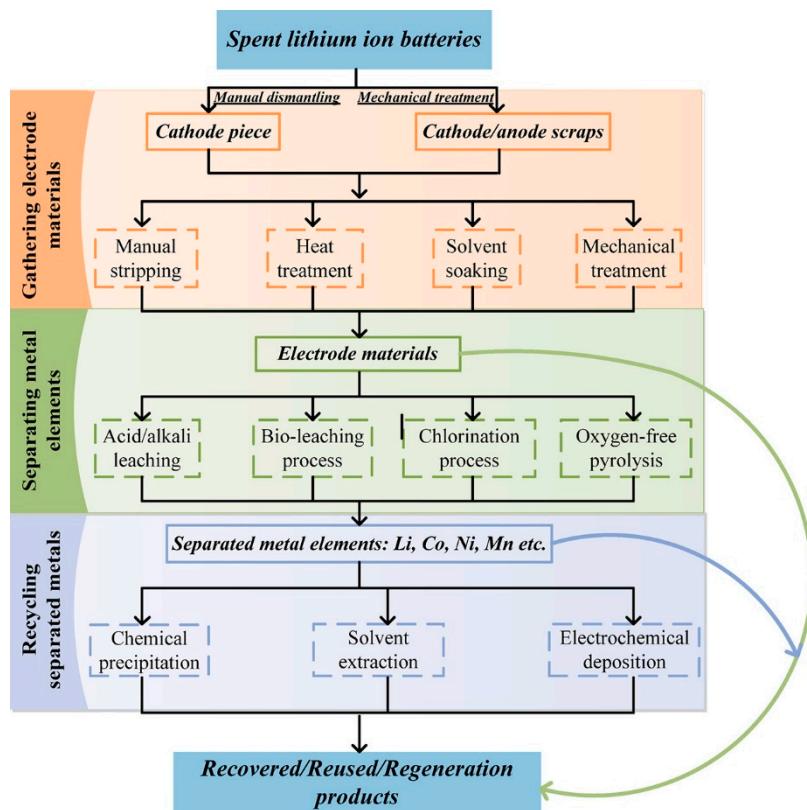


Figure 12. Spent lithium-ion battery recovery process steps [114].

The pyrometallurgical process extracts metals by heating the waste electrodes and adding fluxes to form alloys. Aluminum and lithium are lost in slag if there is no particle size control [113]. Lithium can be recovered by chemical leaching of the slag, but the cost and energy requirements are not economically favorable [113]. Pyrometallurgy requires less pretreatment of the battery scrap, therefore, it has the advantage of having the lowest cost. However, burning plastics will release a variety of highly hazardous chemicals, which leads to secondary pollution [24]. Except for the waste gas, the pyrometallurgy process also suffers from the waste slag (which requires disposal), high energy cost by mechanical treatment, and metal loss [114]. Umicore and BARTEC are the major companies adopting this methodology [24]. Hydrometallurgy consumes less energy and can deal with the low concentration of different metals. Metals are recovered through leaching and extraction at significantly lower temperatures. The advantage of hydrometallurgy is its high recovery rate. The downside of hydrometallurgy is it has many process steps compared to pyrometallurgy [114]. Currently, the majority of the recycling companies are adopting the pyrometallurgical process, mainly because of the lower cost and scalability [24]. However, it is becoming more favorable to use the hydrometallurgical process as higher value can be derived from a broader range of precious metals to offset the processing cost [24]. In China, more than 70% of the recycling processes are primarily hydrometallurgical with the rest of 30% accounted for using pyrometallurgical combined with mechanical disassembly processes [80]. The main difference between hydrometallurgy and direct recycling process is that hydrometallurgy uses strong acids to dissolve and deconstruct the cathode into soluble metal ions, whereas direct recycling retains the cathode crystal

morphology with the aim of reactivating the cathode material. Working with strong acid increases the process costs and complexity [113]. Pyrometallurgical and hydrometallurgical processes can be mixed to deal with waste recycling. Zhang et al. [86] reviewed different methods used in each step of the recycling process including discharge, dismantling, classification, separation of electrode components, and refining of LiCoO₂/graphite and found that the integrated/mixed processes efficiently recover all components from the spent battery. However, this is only for LiCoO₂ LIB chemistry. Direct recycling is also called cathode to cathode recycling, which is particularly attractive for batteries with high value metal elements in the cathode [113]. However, as the feed waste stream will be a mix of different types of battery chemistry, the direct recycling will lead to the generation of a mixture of cathode materials. Unless the retention of the structure of cathode mixture can be regenerated effectively, there is no clear advantage from direct recycling approach. Biological processing is another way to extract metals via microorganism leaching. Driven by green and low secondary pollution, biological or biometallurgical processes have earned more attention in recent years [107]. However, it is difficult to use on a large scale because of the lack of the cultivation medium [24] and possibly susceptible to interference from a variety of chemicals from the broad range of LIB chemistries. Recently, an electrochemical method was used to extract cobalt where the advantage of this method is it does not introduce other substances and can achieve the highest purity of the recovered metal [39]. The industry application of spent LIB recovery process is shown in Figure 13.

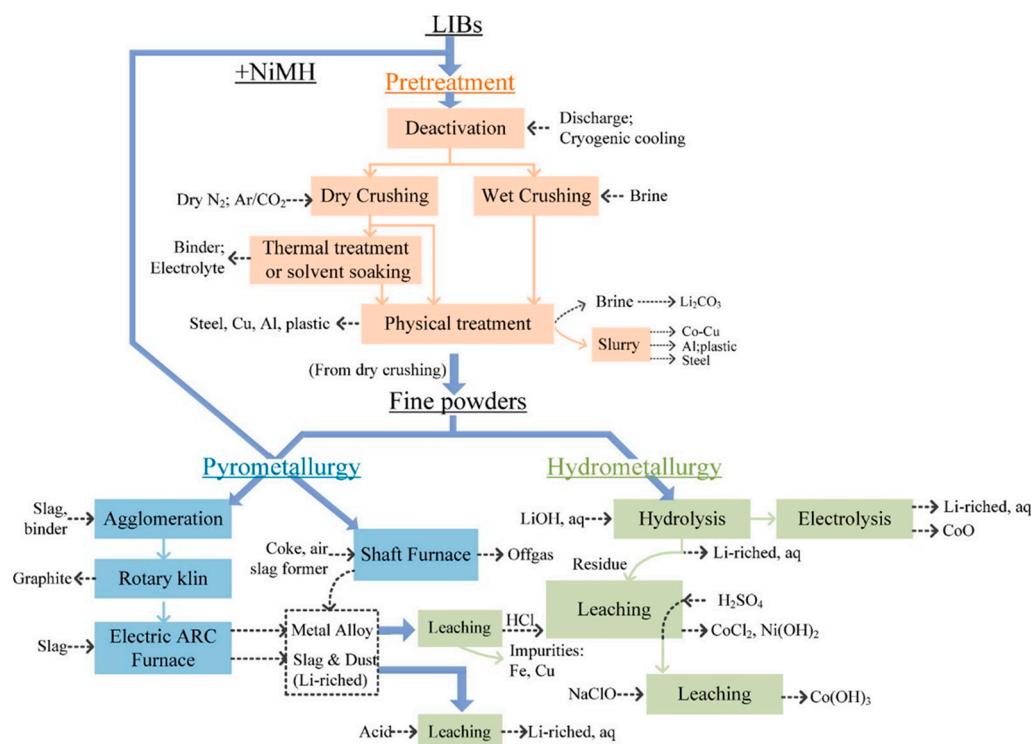


Figure 13. Industrial application of spent lithium ion battery recovery [114].

Xiao et al. [114] reviewed the most recent processes of the major LIB recycling process in detail from environmental perspectives. From this review, it is concluded that: (1) It is important that the safety and health consequences of the release of residual electricity where flammable and hazardous electrolyte and additives should be the highest priority regardless of the process technology chosen; (2) a green low-cost leaching process should be developed to replace the conventional leaching process with strong acid and additives; and (3) to achieve short-route and closed-looped processes by only targeting lithium extraction. As the cobalt component in LIBs is being reduced, it is reasonable to target less of this metal in the waste stream in order to cut the overall process cost [114]. Regardless of

what recovery processes are used for LIB recycling, the objectives of the recycling are the same: to improve yield and purity, to reduce raw material or energy use, to reduce waste produced from the process. However, improvements to these current processes do not guarantee the profitability of LIB recycling as all of these processes rely on the recovery of cobalt as the key metal of commercial interest [26]. It is also critical to make technology advances aimed at reducing recycling costs. Without technology advancement, recyclers may need to charge a fee to accept spent LIBs for recycling or rely on government subsidies or introduced regulations [26]. Currently separating battery waste prior to recycling is not cost effective for industries wanting to enter this sector. An alternative way to contribute to a sustainable battery value chain is to reuse EoL batteries as much as possible before they are disassembled for recycling. This process is called second-life, where the entire battery system can be redeployed in a less demanding application. Second-life batteries may be economic for some battery types and specific applications, but not all. It has been suggested that cobalt-containing batteries should be recycled immediately to boost the cobalt supply for newly manufactured batteries, whereas the other battery types could be reused [113]. An overview of technology adopted by key EV battery recyclers is visualized in Figure 14. For recyclers which use a smelting process, it is easy to recover more than 90% of the cobalt, nickel, and copper from batteries, however, lithium is lost. In Asia, about 80% of LIBs recycling are through a hydrometallurgical process that is claimed to have more than 98% material recovery rate [30]. Cobalt and nickel are usually recovered as sulphates and therefore the purity is very high that enable it to be used in battery manufacturing. The hydrometallurgy process can produce lithium carbonate and it was reported that 99 wt% of Li_2CO_3 with high purity (>99%) which, in principle can be recovered for manufacturing new batteries [115]. However, to achieve high purity battery grade lithium is much more challenging and has yet to be fully addressed using the pyrometallurgical process.

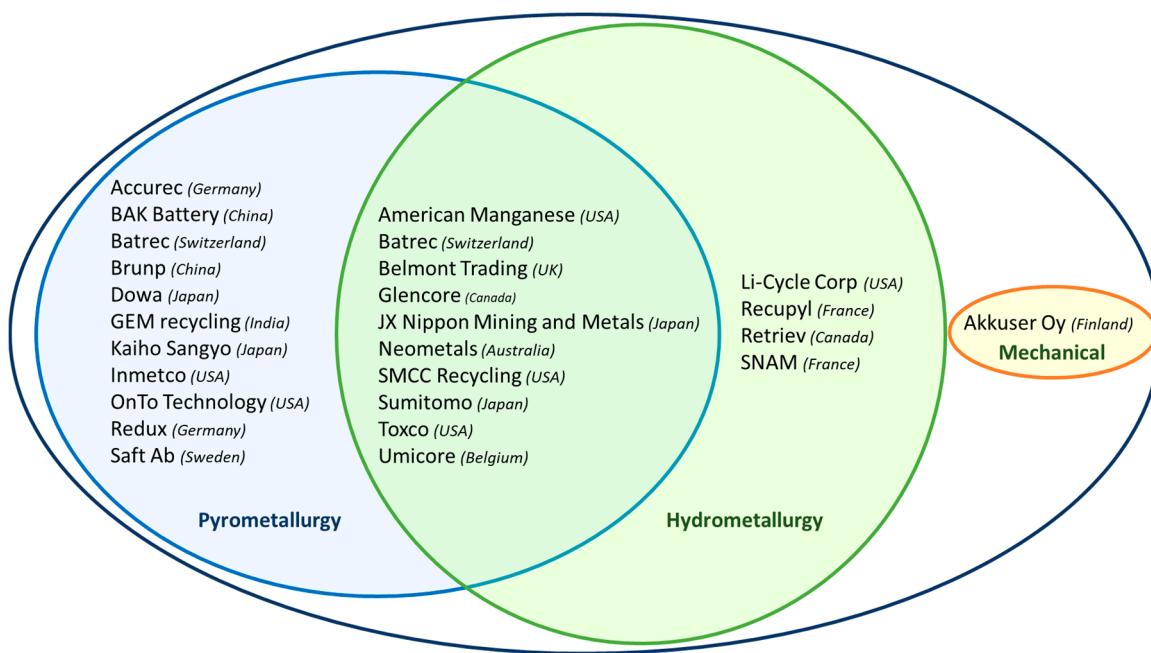


Figure 14. Technologies adopted by major global EV battery recycling companies. Some data from Frost and Sullivan [80] and reference [116].

7. Status of Battery Reuse

From the investigation and discussion in the earlier sections, among the top three battery chemistry types, LABs are cheap, simple, and easy to be reused or recycled, while nickel-based batteries and lithium primary batteries only account for a small fraction of the battery waste stream. These systems make little economic sense for consideration in

second-life applications. In 2018 alone, more than a billion smartphones and more than an additional billion portable electronics devices were sold worldwide [48]. The majority of LIBs present or being collected in the waste stream are from CEs. Currently, the used CE batteries are reused in different applications such as solar lights, counterfeit products, toys, and other suitable products in emerging economies like India [48].

To test these small CE LIBs and reuse them in large-scale applications is less economically viable, therefore, the reuse of these CE batteries has not received the same attention from the scientific community. The interest in reuse (or repurposing) has only started to gain momentum since the growth of and demand for large EV batteries has risen significantly and recycling of these batteries has yet to be properly established. Thus, second-life use has been seen as an economically and environmentally viable means to address this waste stream, until a functioning battery recycling program can be established. Other factors favoring the reuse of EV batteries include:

- Government regulations supporting the reuse of EV batteries in China;
- The 80% residual energy left in the EoL EV batteries according to the EV battery design can be used for less energy demand applications, and
- The growing demand for electrical energy storage could be offset by using second-life batteries rather than newly manufactured products.

The LIB waste stream from EVs consists of 25% of battery electric vehicle (BEV), 36% long-range plug in hybrid electric vehicle (PHEV), and 39% short-range PHEV battery packs in the United States [15]. Although LIBs are dominant in today's EV battery market, the concept of reuse or second-life of EV batteries is not limited to LIBs. Sandia National Laboratory studied the techno-economic viability of using second-life NiMH EV batteries which have degraded to 30 Wh/kg or 45 Wh/kg. The study found that the NiMH batteries performed similarly to new LABs in stationary energy storage applications. This study demonstrated reusing NiMH EV batteries in secondary applications is technically feasible [117]. The foreseen advantages of pursuing battery second-life are illustrated in Figure 15. Similar to LIB recycling, the reuse of EV batteries presently is also complex because of the numerous market and technical challenges, (discussed later).

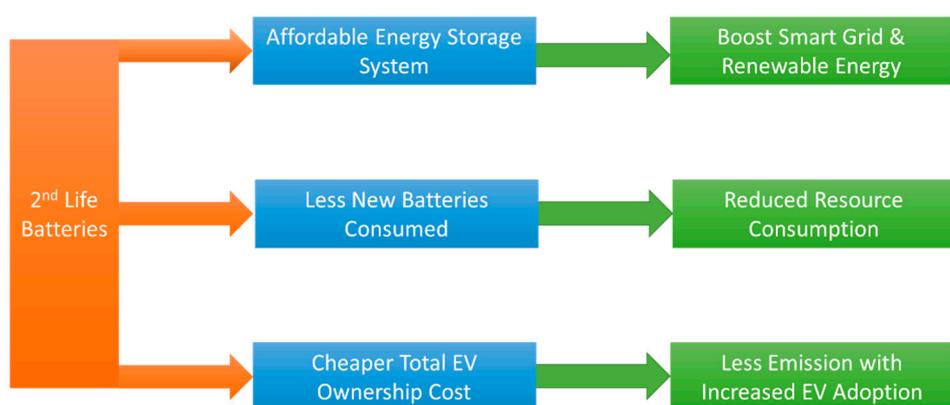


Figure 15. Summary of the primary advantages of using second-life EV batteries.

7.1. The Criteria for EoL EV Batteries' First Life

The EoL for EV batteries was first defined by the US Advanced Battery Consortium (USABC) in 1996 as a 20% drop of cell capacity from the rated value, or a 20% drop from rated power density at 80% depth of discharge (DOD) [118]. It is believed that below this threshold, the surge current drawn in the first few milliseconds during acceleration from the battery pack is too high for the drained battery [48]. However, when these criteria were established, most EVs were powered by nickel-based batteries, which have significantly lower energy density and power capabilities than LIBs [119]. Whether the EV batteries retired meet such criteria is still uncertain and the suitability of the criteria remains questionable. For PHEVs, this threshold is unnecessary as the internal combustion engine

can share the load with the electric drivetrain enabling the batteries to degrade to 80% of rated capacity and still can continue traction service [120]. In 2019, PHEVs contributed 41% of the EV market with the remainder being BEVs [80]. Another simulation study by Saxena et al. [11] also showed that batteries at 30% of initial capacity can already meet the driving need of Americans. They demonstrated that the current EoL EV batteries criterion may be unrealistic as the batteries with 80% remaining capacity are still able to cover the daily travel needs of more than 65% of US drivers, which have the largest average daily travel distance worldwide of about 46 km per day. These studies provide us with exciting insights into the possibility of using EoL EV batteries. As these studies were carried out by simulation without considering the battery degradation, more relevant physical work is needed to help improve the definition of the retiring period of EV batteries [121]. These facts revealed the challenges of pursuing second-life use of batteries and demonstrated the importance of battery health assessment.

7.2. Source of Second-Life Batteries (SLBs)

According to Frost and Sullivan (San Antonio, TX, SAD), there are more than 165 EV models available in the global market. The global stockpile of EoL EV batteries is forecast to exceed 3.04 million packs by 2025 compared with 44,000 in 2018 and it is estimated about 20 million EVs will be sold globally by 2025 [80]. China is leading the EV market with a 51% market share followed by the EU (26%), US (19%), and Japan (4%) [80]. An average EV battery has a life span of 8 to 12 years. Therefore, the share increases in sales of EVs since 2010 is providing a good source of second-life EV batteries as the first generation of retired EV batteries are starting to enter the market. As discussed in Section 3.2.1 in Figure 3a, by 2030 EV batteries will account for over 85% of the entire LIB market, followed by about 10% from energy storage. Therefore, the retired EV batteries will initially be the main focus for battery second life applications. However, the concepts discussed below are equally applicable to EoL batteries from non EV sources.

7.3. Impact of Ownership on Retired Batteries

Under-utilization of batteries is common in many industries, and this leads to discarding a large amount of capacity (or electrical energy) from reasonably healthy batteries. Therefore, the EoL EV batteries can be categorized into: type 1) Reached the end of their first life through the general process of capacity loss; type 2) the vehicle service life ends before the batteries reach the end of their first life. When a battery retires and enters into the secondary life market it is tracked on the battery ownership model (BOM) [119]. The three main BOM are:

1. The EV manufacturer (OEM) is the battery owner and the EV owner leases the battery from the EV manufacturer,
2. Third-party owns the battery and the EV owner leases the battery from the third party, and
3. The EV owner is the battery owner.

For the first two BOM scenarios, the retired battery will most likely have about 80% capacity based on battery performance or defined warranty period. When the EV owner is the battery owner, the battery would only be changed when it is unable to satisfy the customer's need, and therefore is expected to have much less capacity than the recommended 80% threshold. Retired EV batteries could also have higher than 80% capacity if they are from early vehicle failure, e.g., major repairs, collisions etc., [122]. The above-mentioned battery retirement scenarios lead to a wide range of SLBs with different residual capacity and internal resistance values or even different numbers of full-equivalent cycles. Obviously, an EV battery leasing system would be beneficial for the subsequent reuse of SLBs. As discussed in the battery management policy section, China has started to explore setting up a battery-leasing system in 2014. The capacity and internal resistance certainly will impact on the value of the retired battery and the refurbished second-life battery market price [123]. The USABC is planning to introduce a minimum standard

battery life of 15 years [59]. It is essential to have a good understanding of how a battery degrades to the point that its capacity is no longer sufficient for EV use. Therefore, the research efforts in identifying the causes of battery degradation have recently intensified.

7.4. The Price Challenge of Second-Life Batteries

Sandia National Laboratory has studied the cost of second-life batteries in detail [117]. The percentage breakdown of various sectors is shown in Figure 16a. It was identified that the cost of SLB acquisition, labor, general & administrative (G&A), and packaging material are major contributors [117]. Among these costs, the acquisition of the retired EV batteries is the most expensive part accounting for 56% of the total second-life battery cost [117]. Government regulation to curb illegal trafficking of used batteries is critical to protect battery reuse and recycling that prevent extra acquisition costs. Labor costs and general administration are the second biggest cost with each contributing 13% to the cost of battery refurbishment. Whereas another cost study by McLoughlin et al. [124] showed that transportation costs are the second most prominent expense. This may be the result of different definition or classification of the cost components in the two studies. The cost of SLB acquisition could already include the transportation cost, which together with battery materials becomes the biggest overall cost. The labor cost analysis done by Sandia National Laboratory was based on the US market, therefore the labor costs will be much different in other countries. According to the skilled technical labor cost for different countries shown in Figure 16b, the refurbish labor cost in China, Chile, and Poland are comparatively lower, around 5%. As the general administration is also a labor-related expense, it is reasonable to assume that the total battery refurbishment cost could be about 20% less in countries having much lower labor cost compared to the US.

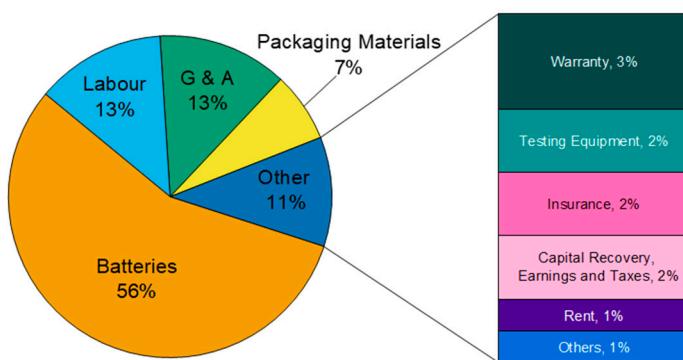
There is a large discrepancy in the battery repurposing among the different cost studies [125], which is summarized in Figure 16c. Among these estimates, Neubauer's values are in between the highest and lowest cost estimates. The cost of second-life battery market price, salvage value, and refurbishment studied by Neubauer et al. [126] are summarized in Table 2.

Table 2. The second-life battery market price, salvage value, and refurbishment cost [126].

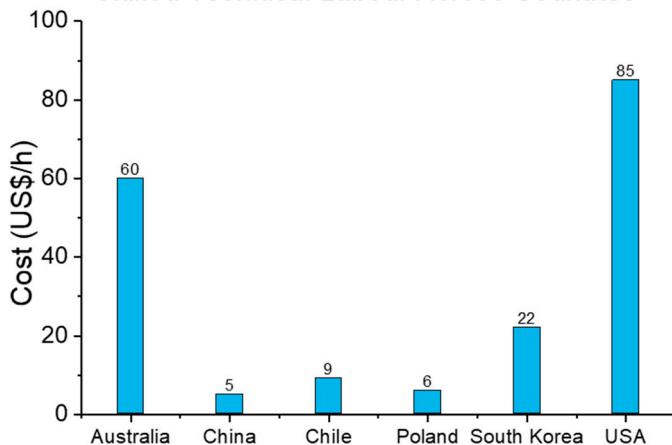
New Battery Price [US\$/kWh]	Second Life DoD	Vehicle	Health Factor	Max Repurposed Battery Sell Price [US\$/kWh]	Used Salvage value [US\$/kWh]	Cost of Refur- bishment [US\$/kWh]
250	60%	BEV75	0.33	83	51	32
		PHEV20	0.29	73	43	30
	50%	BEV75	0.72	180	131	49
		PHEV20	0.65	163	117	46
150	60%	BEV75	0.33	50	24	26
		PHEV20	0.29	44	19	25
	50%	BEV75	0.72	108	72	36
		PHEV20	0.65	98	64	34

The market price for the SLBs ranged from 44 to 180 \$/kWh based on Neubauer's analysis. It was found that small differences in the second-life DoD would have a large effect on the health factor and the salvage value of the SLBs. Neubauer et al. found that repurposing costs can be as low as \$20/kWh if vehicle diagnostics data are available which can be used to support used battery purchase [126]. Because technician labor is a major cost component of the repurposing operation, it is economically impractical to replace faulty cells within modules, therefore minimizing purchases of modules containing faulty cells is critical.

(a) Refurbished Battery Cost Breakdown



(b) Skilled Technical Labour Across Countries



(c) Discrepancies in Second Life Battery Studies

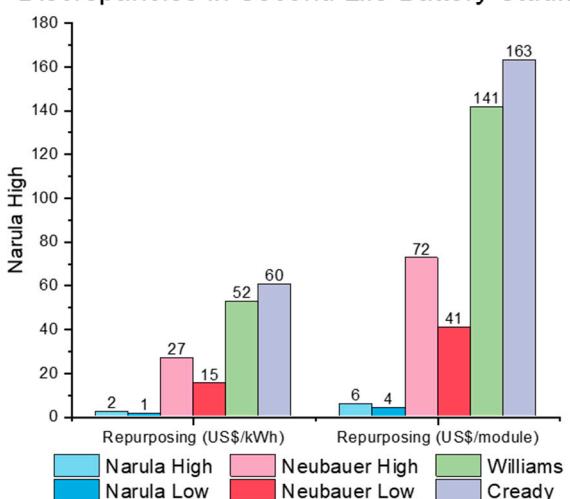


Figure 16. (a) Cost breakdown of second-life EV batteries in percentage [117]. (b) Labor cost in different regions according to [46]. (c) The discrepancy in different cost studies of battery repurposing. Replotted from ref. [125].

However, SLBs are facing a medium to high battery repurpose cost, since the price of EV battery packs keeps falling. The EV battery pack price has fallen significantly from \$1000/kWh in 2010 to \$179/kWh in 2018, with a further drop to \$73/kWh expected by 2030, as battery makers develop more cost-effective processes and the battery production increases [80]. Recent estimates quoted a SLB market price of \$50/kWh versus

\$200–300/kWh for new batteries, indicating that SLBs should remain competitive at least until 2025 [80]. It is worthwhile to point out that when the price for new batteries, the largest cost component of refurbishing batteries, reaches the predicted low levels, the battery acquisition cost will also drop. The expected low price for new batteries is reasonable, and thus SLBs may be economically viable in countries with high work efficiency and low labor cost. Another argument from opposers to SLBs is that battery technology is progressing rapidly with capacity increasing by 3% per year [127]. If a current SLB is at 70–80% of its initial capacity, it will only have a 50–60% of the capacity of a new battery after ten years. It is a common belief that the reuse of EV batteries in second-life applications may have the potential to offset the high initial cost of these batteries today. Neubauer and Pesaran calculated the discount to battery upfront cost and found the second-life use can reduce battery upfront costs from 2.2 to 12% depending on the consumer perception of used batteries [128], which is not a significant figure. When considering the cell failure rate in this model, the maximum discount even reduced to a negligible level of about 5% [129]. Studies were also carried out to test if premature retirement of EV batteries would increase the salvage value and give a larger upfront cost reduction [128,129]. The studies revealed that this scenario is only valid if there are zero refurbishments involved and the customer acceptance of a second-hand product is neglected, which is very hard to meet. Therefore, it was suggested that the preferred way to maximize the cost-efficiency of the batteries would be extending the automotive use as much as possible [119]. As a result, determining and optimizing the upper limit of battery performance has become necessary which is a significant technical gap in the field [119]. Martinez-Laserna et al. [119] indicated that the limited upfront discount will probably be insufficient to change the momentum of EV sales and be a disruptive factor for a faster EV adoption.

7.5. Technical Challenges of Using Second-Life Batteries

Battery performance assessment is critical to predict how long and how well the retired batteries operate and whether they can be deployed in their second-life applications. From an electrochemical point of view, compared with new batteries, SLBs only differ in terms of energy, relating to power capabilities, energy density, and cell to cell heterogeneity [119]. The SLBs present larger cell to cell variability than the new batteries that will be dependent on how these batteries are used throughout its life. The closer the match, the better the restored battery will perform and provide longer lifetime. Packs designed for heavy loads and wide adverse temperature ranges are normally built to $\pm 2.5\%$ tolerance levels. Such a tight tolerance may not be possible with refurbished cells and mono-blocks. Therefore, the inhomogeneity between cells or modules is one of the major technical challenges of using SLBs. Specific control or appropriate battery sizing and energy management strategies are necessary to deal with the large heterogeneity [119]. The extent of heterogeneity determines the potential cost of battery refurbishment. The cell to cell heterogeneity was reported, as expected, to increase as the cell ages [130]. The current assessment of SLBs to determine if the used EV batteries are fit for a second-life application involves visual inspection, verification of battery voltage followed by state of health assessment, capability test or others such as open circuit voltage (OCV), quasi-OCV, and electrochemical impedance spectroscopy (EIS) tests. Cycling studies are commonly used where battery cells are charged and discharged under well-defined conditions to observe the cell capacity, voltage, and physical properties. After testing, batteries with similar characteristics are selected and grouped to form a homogenous second-life battery pack [121].

Another key technical challenge is that many different manufacturers of battery packs utilize different cell form factors (for example cylindrical cells, prismatic cells etc.,) and pack designs. As such a further technical challenge arises for disassembly of packs to access cells and reconstruction of SLB packs to ensure that similar cells, with the homogeneity issues discussed above, are utilized. This can also affect the economics of SLB pack construction. Not all of the different first life battery pack designs will lend themselves to SLB use.

However, this can be remedied by better design of first life batteries by manufacturers to assist with SLB utilization.

7.6. Second-Life Battery Applications and Their Economic Analysis

SLBs can be used in a wide range of residential, commercial, and industrial applications. The residential and commercial use are regarded as small size energy application and the industrial ones usually are large providing support to renewable energy sources such as wind, solar, and transmission. The onsite energy storage in telecommunication energy management also brings opportunities to SLBs, however, it requires high reliability. Market potential and limitation for repurposed LIBs were analyzed by Heymans et al. [131] and summarized in Table 3. Regulated energy pricing reduces the amount of surplus that can be generated by purchasing electricity at a low price and using it during times of peak energy demand. However, the unregulated market provides the opportunity to create significantly higher returns due to price fluctuations. From their economic study, the use of repurposed EV batteries for energy storage and peak sharing can provide cost savings to residential users while shifting power from peak demand to off-peak demand times, therefore reducing strains on the electricity grid. Economic feasibility is marginal without government intervention but would increase to moderate viability with intervention. The economic viability of load shifting capacity depends on both the future cost of SLBs and also the ease of acquisition and installation. Therefore, initially it is necessary to have a government subsidy, likely paid through local energy utilities to homeowners to help offset the investment and promote the adoption of energy storage systems for residential customers. As for the commercial applications, load following applications may be more appropriate than peak sharing applications as the average commercial load is high. The peak sharing model requires 3000–4000 kWh and will need a large number of batteries. For instance, 178–238 reconditioned Nissan leaf SLBs with 70% of their original capacity were used for a peak sharing application [124]. Compared to the commercial load sharing application, the load following applications is more realistic for the reconditioned SLBs, as the load following application only demands 75–100 kWh and the charge/discharge rate of SLBs is more than sufficient to meet the demand [121]. However, the load following application may only be suitable for places with high solar irradiation. The battery backup for small power equipment in remote areas is also regarded as a well-suited application for SLBs [121]. Industrial consumers have a much higher demand than residential and commercial consumers. SLBs could be used to store energy generated by PV and shift the energy from peak to other times of the day (utility load leveling). However, this requires a huge amount of storage capacity (100,000 kWh) and therefore is not very practical [121]. Solar farms for industrial applications require significantly less storage capacity (1000–10,000 kWh), requiring somewhere between 66–595 reconditioned Nissan Leaf batteries as a backup [124]. As for the transmission stabilization application, the reconditioned batteries are regarded not suitable as the charge/discharge rate capabilities will be exceeded when very short bursts of power are required to stabilize the voltage and frequency variations [124]. The economic studies on various applications were reviewed and summarized by Martinez-Laserna et al. [119]. Based on this report, applications according to their profitability are grouped and summarized with critical notes in Table 4. There are numerous applications tested for profitability such as distributed node telecom backup power, decentralized mini- and micro-grids, residential and light commercial load following etc. Three applications were identified as not profitable which includes voltage load levelling/energy load levelling, energy power reliability plus peak sharing and renewables generation grid integration. Many other SLBs applications were deemed controversial in their profitability by different studies, e.g., area regulation, renewable capacity firming, renewable energy time-shift, transmission congestion relief, and transmission support.

Table 3. Markets for repurposed lithium ion batteries [131].

Market Application	Number of Repurposed Packs	Estimated Market Size (Ontario)	Cycle Frequency	Potential for Application	Limitations for Application ^a
Residential	1–2	>3 Million ^c	Daily	Large market and small, easy-to-handle units Market can be incrementally developed	Regulated pricing minimizes savings for user Risk and maintenance must be addressed
Telecommunication towers	5–10	100,000 ^c	Daily and back-up	Motivated for onsite energy storage, and currently has many sites	High reliability demanded by application, and would be difficult to achieve
Light commercial	10–15	10,000–100,000 ^c	Daily	Greater savings due to unregulated electrical pricing	Safety regulations for storing batteries on site must be determined
Office building	30–40	100,000 ^b	Daily	Have the expertise, location and personnel to support the technology Greater savings due to unregulated electrical pricing Can complement generator use	More packs are required Larger application requires significant storage investment Urban locations may create greater risks
Fresh food distribution centers	30–40	10,000–100,000	Daily	Greater savings due to unregulated electrical pricing Large electrical demand with highly controllable equipment will work well with technology Often early adopters if business case can be demonstrated Have the expertise, location and personnel to support the technology	Larger application requires significant storage investment Payback must be clearly demonstrated
Stranded power (renewables)	900	Uncertain (<10) ^d	10–20/Month	Intermittent nature of renewable energy justifies energy storage Have the expertise, location and personnel to support the technology Motivated early adopters allow for greater market penetration of wind and solar	Size of application may use up supply or the supply will not be available Complexity of controlling packs of varying states of health Increased risk of fire
Transmission support	1000	Uncertain (<10)	1/Month	Large energy needs create larger market for batteries Currently users of auxiliary electricity services and thus have some comfort with the application Motivated early adopters to help ease transmission congestion.	Size of application may use up supply or the supply will not be available Benefits can still be achieved working with smaller market applications and customers. Complexity of controlling packs of varying states of health Increased risk of fire

^a Cready et al. (2003), ^b International Energy Agency (IEA) (2007), ^c Statistics Canada (2011) ^d: Environmental Protection Agency (2008) in Reference [131].

Table 4. Summary of economic analysis on the profitability of second-life battery applications. Adapted from reference [119].

Applications	Profitable (Yes/Maybe/No)	Comments
Accelerated calendar life testing	Yes	Profitable
Decentralised mini and microgrid (electricity access in rural areas in emerging markets).	Yes	Profitable
Distributed node telecom backup power	Yes	Profitable
Electric service power quality	Yes	Limited profits agreed by several studies
Light commercial load following	Yes	Profitable
Load-levelling	Yes	Only profitable under most favourable conditions (reduced auxiliary fees or wide price differences between on-peak and off-peak periods)
Power backup for generation asset outages	Yes	Profitable, 1.5 year payback period
Residential demand management (Energy time-shift + peak shaving) + PV	Yes	Profitable concluded by different studies. Savings surplus the costs of the batteries; best case with 6 years payback period
Residential load following	Yes	Profitable
Smart grid load dispatch	Yes	Profitable, Utilities obtain profits from second life use and EV owners perceive a reduction on the LCOE of the batteries of about 20%
T&D upgrade deferral	Yes	Limited profits
UPS	Yes	Profitable
Voltage support	Yes	Limited profits or profitable concluded by different studies
Wind generation grid integration, Short duration	Yes	Limited profits agreed by several studies
Area regulation	Maybe	Limited profits
Area regulation + Spinning reserve capacity	Maybe	Limited profits or not profitable from different studies
Demand charge management	Maybe	Limited profits or not profitable from different studies
Electric service reliability	Maybe	Limited profits or not profitable from different studies
Electric supply capacity	Maybe	Limited profits or not profitable from different studies
Electric supply reserve capacity	Maybe	Limited profits or not profitable from different studies
Energy time-shift	Maybe	Limited profits or not profitable from different studies
Load-following	Maybe	Limited profits or not profitable from different studies
Renewable capacity firming	Maybe	Limited profits or not profitable from different studies
Renewable energy time-shift	Maybe	Limited profits or not profitable from different studies
Substation on-site power	Maybe	Limited profits or not profitable from different studies
Time-of-use energy cost management	Maybe	Limited profits or not profitable from different studies
Transmission congestion relief	Maybe	Limited profits or not profitable from different studies
Transmission Support	Maybe	Limited profits or not profitable from different studies
Load Levelling/Energy Load Levelling/Energy	No	Not profitable
Power reliability + peak shaving	No	Not profitable
Wind generation grid integration, long duration	No	Not profitable

7.7. Activities of EV Battery Reuse

As EV battery recycling is still very expensive, their reuse is considered to be a more lucrative option for EV and battery makers. As the recycling technology continues to evolve and improve (including the currently lucrative reuse), it is expected that recycling facilities for EV batteries will set up across the world to function on a full scale from 2021 onwards [80]. Several large automotive manufacturers, academia, and local governments are showing an increasing interest for battery second-life use. EV companies have begun to form partnerships with battery manufacturers and recycling companies to develop a

market around second-life batteries. There has been plenty of research and pilot projects for repurposing used EV batteries into grid-scale stationary energy storage by large automotive companies. Demonstration projects have been deployed in numerous places to prove the technical viability of using SLBs. Because of the nascent EV market leading to an initially small amount of used battery packs, the majority of projects are in the pilot stage [48]. Figure 17 shows where the EV batteries are being tested and reused globally according to Bloomberg business news. The use of SLBs in the energy storage sector not only proved to be profitable but also benefits from government incentives. For example, the US federal regulations offered up to 30% incentive (relative to total project cost) for energy storage projects deployed with solar PV systems in 2019. The EU also offers incentives through the Horizon 2020 program in the region for projects related to energy storage on the grids [132]. It can be seen there are numerous large SLB application projects, especially in the EU where they are related to grid energy storage. Table 5 summarizes battery second-life pilot and commercial projects between 2012 and 2017 followed by examples of more recent industrial reuse of SLBs from 2018 to 2020 showing the trend of second-life battery reuse in the energy storage and grids applications.

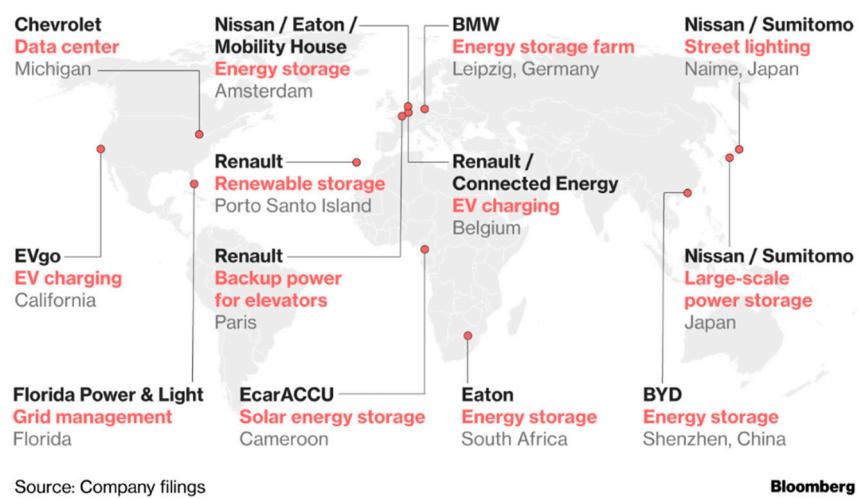


Figure 17. Testing of EV batteries for different second-life applications, Bloomberg [133].

Table 5. Examples of battery second-life pilot and commercial projects between 2012 and 2017 [38].

OEM	B2U Partner/Service Provider	EV Model	Capacity	B2U Application	Country
Daimler	GETEC, The Mobility House, Remondis	Smart	13 MWh	Renewable energy	Germany
GM	ABB	Volt	50 kWh/25 kW	Power supply	USA
GM	ABB	Volt	n/a	Renewable energy	USA
Renault	Eco2Charge	Kangoo ZE	66 kWh	Renewable energy	France
Nissan	Eaton	Leaf	4.2 kWh	Residential energy storage	UK
Nissan	Eaton & The Mobility House	Leaf	4 MWh/4 MW	Peak shaving, Backup power	Netherlands
Nissan	Sumitomo	Leaf	400 kWh/600 kW	Renewable energy	Japan
Mitsubishi & PSA	EDF & Forsee Power	Peugeot Ion, C-zero & iMiev	n/a	Renewable energy	France
BMW	UC San Diego	Mini-E	160 kWh/100 kW	Renewable energy	USA
BMW	Vattenfall & Bosch	ActiveE & i3	2.8 MWh/2 MW	Renewable energy	Germany
BMW	Vattenfall	i3	12 kWh/50 kW	Fast charging	Germany
Renault	Connected Energy	Zoe	50 kWh/50 kW	Fast charging	UK

7.8. Recent Industrial Activities of Reusing Second-Life Batteries

BMW is actively exploring SLB applications aiming for a fully sustainable supply-chain. BMW is collaborating with Northvolt, Europe's largest EV battery factory and Umicore, a mineral processing and battery recycling company, to develop battery reuse and recycling systems. BMW, Bosch, and Vattenfall formed a joint venture in 2016 to form a large storage facility in Germany producing a total capacity of 2 MW using 2600 retired batteries from more than 100 BMW EVs to stabilize the grid and reduce the impact of peak demand [134]. In 2017, BMW announced a strategy to reuse batteries from their i3 cars in wall mounted home storage units. In 2019 BMW, Umicore, and Northvolt announced to reuse most of the retired EV batteries in the renewable energy storage sector [135]. German car manufacturer Daimler also joined its subsidiary, Mercedes-Benz Energy, to launch projects using EV battery packs for stationary energy storage. In total, three energy storage plants made of retired EV battery systems were connected to the grid in Germany [136]. One project turned a retired 330 MW of installed capacity (9.8 MWh of energy capacity) using 1920 battery modules from EV battery packs [136]. A significant public demonstration of the ability of repurposed batteries to provide energy storage and grid service has been carried out in the Netherlands, where a 3 MW (nominal power)/2.8 MWh (nominal capacity) energy storage system was installed for the Johan Cruyff Arena (Amsterdam) in 2018. Apart from energy storage system applications, in 2019 Audi started using retired second-life batteries from its cars on forklift trucks [18]. It was claimed using LIBs boost the driving performance of forklift trucks, as the LIBs can maintain a constant speed on a slope which is not possible with LABs. Another advantage of using the lithium SLBs is that they can be easily charged so that the forklift trucks are not out of commission for long periods. The required SLB pack size and weight are similar to the LABs therefore no major adjustment to the forklift truck is required.

Japan opened its first plant specializing in the reuse and recycling of LIBs in 2018 [21]. Operated by 4R Energy Corporation, collaborating with Relectrify in late 2018 to develop second-life battery storage solutions, including the repurposing of used batteries from the Nissan Leaf [137]. The Japanese energy storage company Connexx Systems has been testing the feasibility of using repurposed EV batteries in stationary energy storage system for photovoltaic power generation since 2018 [138]. Toyota isis planning to install their retired EV batteries outside 7-Eleven stores [21]. The hybrid batteries will store power from solar panels to help power these stores. Hyundai Motor Group collaborated with Finnish energy technology group Wärtsilä in 2018 to repurpose second-life plug-in vehicle batteries as stationary energy storage products for both grid scale and commercial scale. Hyundai is also building a 1 MWh energy storage system for one of its steel factories using retired batteries from its Ioniq Electric and Soul Electric vehicles [139]. Honda collaborated with recycling company SNAM and announced an EV battery second-life reuse plant for energy storage systems in 2020 [140]. Through General Motors' pilot program, in partnership with American residential energy provider Duke Energy, the Chevy Volt EoL EV LIBs are being tested in grid demonstrations to investigate the cost efficiencies and utility of the system, and to determine if the batteries can be used in wider applications, such as powering homes during brownouts and blackouts [136]. A quick battery testing technology was developed by a London-based start-up company, Aceleron, to help identify the right second-life applications for SLBs from CEs, EVs, and medical devices, where the company uses the technology to resell certified SLBs [141].

As recycling is not currently very profitable, China has found an interesting solution for SLB applications in the telecommunication sector. China Tower, the world largest operator of telecommunication towers has ceased the future purchasing of LABs. The existing LABs that provide energy back-up for 98% of 2 million telecommunication towers (54 GWh battery storage demand) base stations will be replaced by second-life LIBs. To meet the demand of two million SLBs, China Tower partnered with more than 16 major Chinese EV and battery manufacturers [19], and are developing recycling technologies and business models.

8. Conclusions and Outlook

With primary and secondary batteries, rechargeable batteries remain the dominant market share with 73.8% of the total global battery market. Of the different types of secondary batteries, lead-acid and lithium ion are the top two battery chemistry types that occupy most of the rechargeable battery market with nickel-based batteries supplying only about 4% of the market. Because of the toxicity of cadmium and regulations associated with its use, NiCd batteries slowly diminish in the battery market. The dramatic increase in the adoption of electric cars in recent years and the predicted significant growth in electric mobility and energy storage applications have driven the high demand for EV batteries. In particular, EVs interest in LIBs and NiMH batteries for use in other applications raised concerns around the environmental impact and waste management of EoL batteries. Today, LABs are a cost-effective and robust battery system that contribute the biggest share in the global battery market where it is widely used in vehicle starting, lighting, ignition (75%), and energy storage backup (25%). LABs continue to grow because of their low cost, but at a much slower rate than its competitor, LIBs, which is expected to contribute to 85% of the total rechargeable battery growth in the next four years. Geographically, China shares more than half of the battery demand with its future demand expected to increase by nearly ten times by 2030 but is expected to see a decline in market share when countries develop their own battery industries.

In the battery waste stream, LABs comprise of more than 90% of the world's lead consumption and developed countries have managed to achieve 99% recycling rates, whereas in developing countries the implementation of strict regulations has dramatically improved the collection, recycling, and fewer batteries ending up in landfill. This study also supports that lead acid and NiMH battery recycling are a profitable business that, in 2019 accounted for 86% and 4% of the global secondary battery recycling revenue, respectively. Currently, the profitability of LIB recycling is marginal in Asia or not currently economically viable in countries with low feedstocks. Although LIBs contribute to a large amount of battery sales in recent years and with their longer life span the volume of LIBs in the EoL waste stream is still limited in some regions. For the emerging LIB recycling industry, a lack of consistent supply of EoL batteries is a significant economic barrier. This issue is further complicated in many jurisdictions, where EoL batteries are exported to Asian countries. Currently, the main waste stream of LIBs is from CEs which are normally small in device size. It is expected that with the retirement of lithium EV batteries in the near future, the recycling of LIBs will experience a dramatic increase globally as several supply chain gaps will be resolved. Currently, most of the collected EoL LIBs from the EU and US are shipped to Asia, where the recycling rate of LIBs has increased to more than 50% globally last year. There are great concerns about the possible price decline in cobalt and lithium resources. The market trend of adopting less cobalt chemistry and the growing attention of competing energy sources, such as the hydrogen fuel cell, brings future uncertainty to the profitability of LIB recycling. This study reveals that batteries that use the NMC chemistry are predicted to have significant end-use increase and become the dominant chemistry (48%) by 2025 in LIBs. However, because of the current cost and resource insecurity of cobalt, the percentage of valuable nickel and lithium is expected to increase in next generation LIBs; for example, the sharp price decline in critical metals used in LIBs in the past two years is mainly due to large investment and oversupply derived from the overestimation of EV adoption. With the expected future production growth and demand of battery raw material industries, the prospect of long-term continuous sharp price drops of critical metals required for current and next generation LIBs is still low. As LIB development is shifting to low Co and high Ni and Li chemistry, combined with extended producer responsibility and government incentives for waste management, this would bring opportunities for profitable recycling. Because of the enormous quantities of EoL LIBs, recycling of LIBs will not be an option but a necessity and a profitable business when the large volumes become available to support reuse and recycling ecosystems. Regarding recycling technology, recycling of lead acid and nickel metal hydride batteries

are comparatively simple and mature technologies. Although LIB recycling is currently a challenge, it also presents new opportunities. With recent technology developments, good extraction rates of valuable elements in LIBs continue to be developed, for all metals in interest. Different from LIBs derived from CEs, the recycling pretreatment for EV batteries such as the disassembly and sorting requires intensive labor, which is difficult to resolve by automation because of the lack of LIB standardization and proper battery identification. These issues have started to be addressed by several countries and companies by changing battery design for easier dismantling and implementing tracking systems by using a unique battery ID, which will be an invaluable help for future reuse of SLBs and LIB recycling.

In the field of legislation, Pd-, Hg-, and Cd-containing batteries are under strict regulation as toxic and hazardous materials are banned from landfill. Globally, LIBs are not currently considered hazardous materials, but in a few regions and states, it has been banned from landfill that have encouraged reuse and recycling activities. The major battery production regions like China, EU, US, and Japan have all implemented “extended producer responsibility” to promote waste battery reuse and recycling. The push on EV battery standardization for easy removal and dismantling has also recently been proposed in several government jurisdictions.

Because of the growing demand in energy storage and financial incentives, EoL EV batteries, in particular, LIBs and NiMH batteries are considered as economically viable ideal options for energy storage applications in the next few years. The challenges of using SLBs versus new battery systems are the decline of new batteries prices, less homogeneous packs, lack of product availability for large applications, and the relatively complex evaluation of battery state of health and predicting the performance of SLBs. From the cost breakdown analysis of battery refurbishment and survey of economic analyses, this review suggests that the use of SLBs is profitable for some applications and could remain profitable in countries with high productivity and low labor cost even if the likelihood of further price declines for new batteries. From reviewing the activity in the area of battery reuse, it was found that the reuse of SLBs has attracted growing interests and also significant actions by prominent global EV manufactures, particularly for combined PV/energy storage applications. Partnership and collaboration between battery makers, EV manufacturers, and battery recyclers are forming globally, which will eventually help accelerate battery reuse and recycling industries and supply chain toward a battery Circular Economy with higher efficiency.

In addition, it was noted that the electric mobility application of batteries is forecast to grow at a much more rapid rate than that of energy storage over the next ten years. Although there is a lag in the retirement of EV batteries, there may not be enough suitable energy storage applications to absorb the entire capacity of the retired EV batteries if the expected trend continues. At this transition point, it has been promoted by some groups and researchers that batteries with high recovery value or unsuitable for second-life will inevitably be recycled immediately to extract the critical metals to be used in next generation battery manufacturing. In this scenario, the multi-step hydrothermal processes could be simplified to just recover the high value elements to further cut down the capital and recycling operation cost to suit the shift in battery chemistry. Based on some of the economic studies, the most viable way is to use a battery as long as possible, without intensive refurbishment. A so-called battery CV or passport tracking system to track the battery use history internally through battery management systems and flow history externally through unique ID numbers is the key to reduce cost and improve battery management efficiency. It is anticipated that battery standardization, battery tracking, and EV battery reuse could be the future trends to contribute to the operation of global battery value chains.

Author Contributions: Conceptualization, A.I.B., G.E.C. and P.J.M.; methodology, O.P., Y.Z., T.R., A.I.B., A.F.H., G.E.C.; writing—original draft preparation, O.P., Y.Z. and A.I.B.; writing—review and editing, G.E.C., P.J.M., A.F.H. and T.R.; supervision, A.I.B., G.E.C. and P.J.M.; project administration, A.I.B.; funding acquisition, A.I.B. All authors have read and agreed to the published version of the manuscript.

Funding: O.P. would like to thank the Australia Federal Government for providing funding through the Australian Government Research Training Program Scholarship.

Data Availability Statement: As this is a literature review article there is no experimental/modelling data involved and all external sources involving the use of data have been disclosed.

Conflicts of Interest: The authors declare no conflict of interest.

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