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Reuse and Recycling: Environmental Sustainability of Lithium-Ion Battery Energy Storage Systems

An Energy Storage Partnership Report

Reuse and Recycling

Environmental Sustainability of Lithium-ion Battery Energy Storage Systems

This report of the Energy Storage Partnership is prepared by the Climate Smart Mining Initiative and the Energy Sector Management Assistance Program (ESMAP) with contributions from the Faraday Institution, the National Renewable Energy Laboratory, the National Physical Laboratory, the Chinese Industrial Association of Power Producers, the Korea Battery Industry Association, the Indian Energy Storage Alliance, the Global Battery Alliance, the Belgian Energy Research Alliance, the UNEP DTU Partnership, and the World Bank Group. The Energy Storage Program is a global partnership convened by the World Bank Group through ESMAP to foster international cooperation to develop sustainable energy storage solutions for developing countries. For more information visit: https://www.esmap.org/energystorage

ABOUT ESMAP

The Energy Sector Management Assistance Program (ESMAP) is a partnership between the World Bank and 18 partners to help low and middle-income countries reduce poverty and boost growth through sustainable energy solutions. ESMAP's analytical and advisory services are fully integrated within the World Bank's country financing and policy dialogue in the energy sector. Through the World Bank Group (WBG), ESMAP works to accelerate the energy transition required to achieve Sustainable Development Goal 7 (SDG7) to ensure access to affordable, reliable, sustainable, and modern energy for all. It helps to shape WBG strategies and programs to achieve the WBG Climate Change Action Plan targets. https://esmap.org

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ACRONYMS

Ah	ampere hour
CIAPP	Chinese Industrial Association of Power Producers
EOL	end of life
ESMAP	Energy Storage Management Assistance Program
ESP	Energy Storage Partnership
EV	electric vehicle
GBA	Global Battery Alliance
GHG	greenhouse gas
HEV	hybrid electric vehicles
IEA	International Energy Association
IRENA	Internaltion Renewable Energy Agency
ISEA	Indian Energy Storage Alliance
KBIA	Korena Battery Industry Association
LiBESS	Lithium-ion battery energy storage systems
Li-ion	lithium-ion (battery)
LTSA	long-term service agreement
mAh	mega ampere hour
MW	megawatt
MWh	megawatt hour
NREL	National Renewable Energy Laboratory
NPL	National Physical Laboratory
OEM	original equipment manufacturer
PV	solar photovoltaic
SOC	state of charge
UNEP/DTU	United Nations Environment Program (Danish Technical University)

All currency in United States dollars (US$, USD), unless otherwise indicated.

EXECUTIVE SUMMARY

The objective of this report is to provide an overview of the state of affairs with regards to reuse and recycling of lithium-ion or Li-ion batteries, in order to assess if and to what extent developing countries can and should play a larger role in this burgeoning area.

The state of research and practice with respect to the recycling and/or reuse of Li-ion batteries is at a critical stage of development. Only now are countries, mostly in Europe, Asia and North America, beginning to seriously intensify plans for a wholesale transition of their society's vehicular infrastructure from fuel injection to the electric motor engine. China, South Korea and Japan have explored end-of-life scenarios for electric batteries for over 20 years and are already developing a robust recycling infrastructure for Li-ion batteries, including reuse capacities as a secondary stationary power source/backup. Europe is starting to catch up, as is the United States. Africa and Latin America have so far done very little to develop a recycling infrastructure with respect to batteries for electric vehicles (EVs).

The motivation for developing countries to become integral contributors in a circular economy is simple: theoretically at least, research indicates that taking on such an approach is both economically and environmentally more effective. At the right scale, recycling/reusing Li-ion batteries is cheaper and cleaner (Ambrose et al. 2014). Since these products contain materials that are potentially hazardous to the environment, it is vital that a system is established for the effective management of the batteries at the end of their useful life, with a view to ultimately phase out disposal in landfills or waste dumps. In addition, for those countries lacking copper, cobalt, and other metals needed for building clean energy technologies, a robust recycling regime may enhance their strategic reserves of these metals, which are of crucial relevance to climate action.[1]

The goal of a global renewable energy storage is to build a market-oriented and green energy storage technology innovation system that considers: long-term design; low carbon manufacturing; safe operation and maintenance; and green recycling. In the context of developing countries, this report proposes short-term recommendations on awareness raising, capacity building, incentives for collection, establishment of specific recycling/reuse regulatory regime (incl. collection), and longer term recommendations on the development of distribution/transportation centers, setting of bold public policy measures, harmonized standards, and development of liability guidelines.

PREFACE

This report is developed by the Climate Smart Mining Initiative, under the coordination of the Energy Storage Partnership (ESP) and in particular, Working Group 7 of the ESP whose mandate is to explore the challenges and opportunities of recycling and reusing Li-ion batteries in developing countries. Participating institutions, include the Faraday Institution, the National Renewable Energy Laboratory, the National Physical Laboratory, the Chinese Industrial Association of Power Producers, the Korea Battery Industry Association, the Indian Energy Storage Alliance, the Global Battery Alliance, the Belgian Energy Research Alliance, the UNEP DTU Partnership, and the World Bank Group.

The Climate Smart Mining initiative[2] supports the responsible extraction, processing, and recycling of minerals needed for low carbon technologies by reducing their climate and material footprints from extraction to end-use through increased technical assistance and investments in mineral-rich developing countries. This means adopting a circular economy approach that works to maximize recycling and reuse opportunities while recognizing that more extraction and processing of primary metals will still be required if we are to meet the long-term global climate targets set in the 2016 Paris Climate Agreement. By mid-century, the industry must develop and implement zero carbon practices applicable to all production and energy needs that involve physical impacts (such as tailings), and these practices must be on a scale that dwarfs current efforts. Additionally, the industry should robustly explore nature-based climate solutions.

The Energy Storage Partnership, convened by the World Bank and hosted at the World Bank's Energy Sector Management Assistance Program (ESMAP)[3], brings together international organizations to help develop safe, sustainable energy storage solutions tailored to the needs of developing countries. By connecting stakeholders and sharing international experiences in deploying energy storage solutions around the world, ESP helps bring new technological, regulatory, and capacity building solutions to developing countries, as well as developing new business models that leverage the full range of services that storage can provide. Taking a technology neutral approach, ESP is helping to expand the global market for energy storage, leading to technology improvements, more integration of renewable energy, and accelerating cost reductions over time.

This report will be organized along three related themes:

- Introducing the issue and identifying the technology attributes most relevant for environmental sustainability and a circular economy;
- Taking stock of current reuse and recycling practices and relevant knowledge to date; and,
- Recommendations for policy measures and future research in developing countries

Plans are underway for workshops and experts' roundtables to be held later this year, initially in Africa, followed by a roadmap to expand opportunities for reuse and recycling of batteries in developing countries.

This report was written by John Drexhage (Lead Author, Climate Smart Mining Initiative, World Bank), Tarek Keskes (Energy Sector Management Assistance Program, World Bank), and Kirsten Lori Hund (Climate Smart Mining Initiative, World Bank); with invaluable input from: Matthew Keyser (National Renewable Energy Laboratory), Andrew Deadman (National Physical Laboratory), Nick Smailes (The Faraday Institution), Mathy Stanislaus (Global Battery Alliance, World Economic Forum), Daniele La Porta (Climate Smart Mining Initiative, World Bank), Gael Gregoire (International Finance Corporation), Peter Mockel (International Finance Corporation), Jonathan Eckart (Global Battery Alliance, World Economic Forum), Paul Anderson (The Faraday Institution), Emma Richardson (National Physical Laboratory), Rahul Walawalkar (India Energy Storage Alliance), Debmalya Sen (India Energy Storage Alliance), Yu-Tack Kim (Korea Battery Industry Association), Yongchong Chen (Institute of Electrical Engineering Chinese Academy of Sciences, China Energy Storage Applications Association), Hao Liu (Institute of Electrical Engineering Chinese Academy of Sciences, China Energy Storage Applications Association), Dandan Liu (Institute of Electrical Engineering Chinese Academy of Sciences, China Energy Storage Applications Association), Leen Govaerts (Belgian Energy Research Alliance), Subash Dhar (UNEP DTU Partnership), Sunday Leonard (Scientific & Technical Advisory Panel of the Global Environment Facility, UNEP), and Shane Thompson (Consultant). Special thanks to all of the Energy Storage Partnership partners who participated in the peer review process.

NOTES

1. The issue of strategic mineral reserves is currently a focus of more mature economies. Its utility in the context of least developed economies remains open to question.
2. The Climate Smart Mining Initiative sits within the Energy and Extractives Global Practice of the World Bank, and is a collaboration between the World Bank and the IFC, with support from the Dutch Government, Anglo American, Rio Tinto and GiZ.
3. The Energy Sector Management Assistance Program (ESMAP) is a global knowledge and technical assistance partnership administered by the World Bank and funded by Australia, Austria, Canada, Denmark, the European Commission, Finland, France, Germany, Iceland, Italy, Japan, Lithuania, Luxembourg, the Netherlands, Norway, the Rockefeller Foundation, Sweden, Switzerland, and the United Kingdom, as well as the World Bank. ESMAP's mission is to assist clients—low and middle-income countries—to increase know-how and institutional capacity to achieve environmentally sustainable energy solutions for poverty reduction and economic growth.

1 LiBESS AND THE CIRCULAR ECONOMY

The call for urgent action to address climate change and develop more sustainable modes of energy delivery is generally recognized. It is also apparent that batteries, both in the transportation and the power sectors, need to play a predominant role if the global community is to limit global warming to 2°C. Simply put, nations' efforts will focus largely on electrifying transportation systems to be supported by power systems that deliver low carbon energy, using a range of renewable technologies. Stationary batteries will play a critical role in not only providing direct energy services, but also in acting as backup providers when renewable resources are only able to provide intermittent services, dependent on local climatic and other circumstances.

To integrate these variable renewable resources into grids at the scale necessary to mitigate climate change, energy storage will be key.[1] The increased use of wind and solar power with storage can help decarbonize power systems; expand energy access; improve grid reliability; and increase the resilience of energy systems.

The requirements of developing countries' grids are not yet met by the current energy storage market—which is driven by the electric vehicle (EV) industry—even though these countries may show the greatest potential for battery deployment. Most mainstream technologies cannot provide long duration storage or withstand harsh climatic conditions and low operation and maintenance capacity.

There is a clear need to catalyze a new market for batteries and other energy storage solutions suitable for a variety of grid and off-grid applications and deployable on a large scale. To enable the rapid uptake of variable renewable energy in developing countries, the World Bank Group convened the Energy Storage Partnership (ESP), that will foster international cooperation on:

- Technology Research Development and Demonstration Applications
- System Integration and Planning Tools
- Policies, Regulations, and Procurement
- Enabling Systems for Management and Sustainability

With respect to reused and recycled batteries, the literature is clear: compared to other battery types, there is a much greater potential in the adoption of second-life Li-ion batteries, mostly due to the rapid uptake of Li-ion batteries for electric vehicles world wide and the consequent pressure to devise end-of-life (EOL) strategies for these products (Prescient & Strategic Intelligence 2020). As an illustration of EVs projected growth, the International Renewable Energy Agency (IRENA) estimates that for the Paris Climate Agreement target to be met, EVs penetration in the market place will need to climb rapidly from 6 million in 2019 to 157 million by 2030 and 745 million EVs by 2040 (Prescient & Strategic Intelligence 2020).

In exploring the opportunities and challenges facing developing countries in the reuse and recycling of Li-ion battery energy storage systems (LiBESS), this chapter will summarize the history of the battery, review the main contending battery technologies, and then provide an overview of the different Li-ion batteries currently in operation. The chapter concludes with a discussion of the circular economy and its technology attributes relevant for prolonging the performance of LiBESS.

THE BATTERY: A BRIEF HISTORY[2]

A battery essentially provides for the conversion of stored chemical energy into electrical energy. The first modern battery, as we know it, was invented by the Italian physicist Alessandro Volta in 1800. Batteries have always played a useful role in capturing and storing energy, however, their role took on a completely new profile with the introduction of the lead-acid battery in the modern internal combustion engine. The lead battery is the oldest, rechargeable battery consumed globally and, until 2015, was the most popular.

Over the last few decades, the lead battery has given way to alternative forms of stored energy, in particular, the Li-ion battery. Lead-acid batteries do not deliver very effectively for advancing electronic technologies—from cellphones to electric motor vehicles. The Li-ion battery was developed to address those challenges. It surpasses the lead-acid battery in all technical storage variables, including energy capacity, efficiency, and life span (Alarco and Talbot 2015). Invented in 1980 by the American physicist Professor John Goodenough, it uses one of the lightest known elements, with a very high electrochemical potential, to produce among the highest possible voltages in an extremely compact form. In this new battery, lithium is combined with a transition meta—such as cobalt, nickel, manganese, phosphorus, or iron—and oxygen to form the cathode.

Currently, Li-ion technologies benefit from massive recent investment in research and large-scale manufacturing of consumer goods and electric vehicles. These efforts dwarf any devoted to alternative chemistries, such as that of the lead-acid battery.

By 2015, owing to its superior technological capacities, delivered at a competitive price, Li-ion battery technology had displaced lead-acid as the dominant design for frequency regulation and the integration of renewables. Figure 1.1 provides some additional information with respect to the new generation of batteries.

Li-ion batteries continue to evolve. New innovative compounds can store more lithium in positive and negative electrodes and will facilitate greater storage and delivery of energy. As a result of this continued improvement, a new generation of advanced Li-ion batteries is expected to be deployed before the first generation of solid-state batteries[3]. These advanced Li-ion batteries will be ideal for use in applications such as energy storage systems for renewables and transportation where high energy, high power, and safety are mandatory.

The two main types of Li-ion battery offer positive and negative electrode options, respectively. Some are more attuned to providing transportation related services while others are more adept at providing stationary power (Marsh 2019). Tables 1.1 and 1.2 delineate batteries using both electrode options.

Negative electrode materials are traditionally constructed from graphite and other carbon materials, although newer silicon-based materials are being increasingly used. These materials are abundant and electrically conducting, and can intercalate lithium ions to store electrical charge with modest volume expansion roughly 10% (Manhart et al. 2018, p. 17).

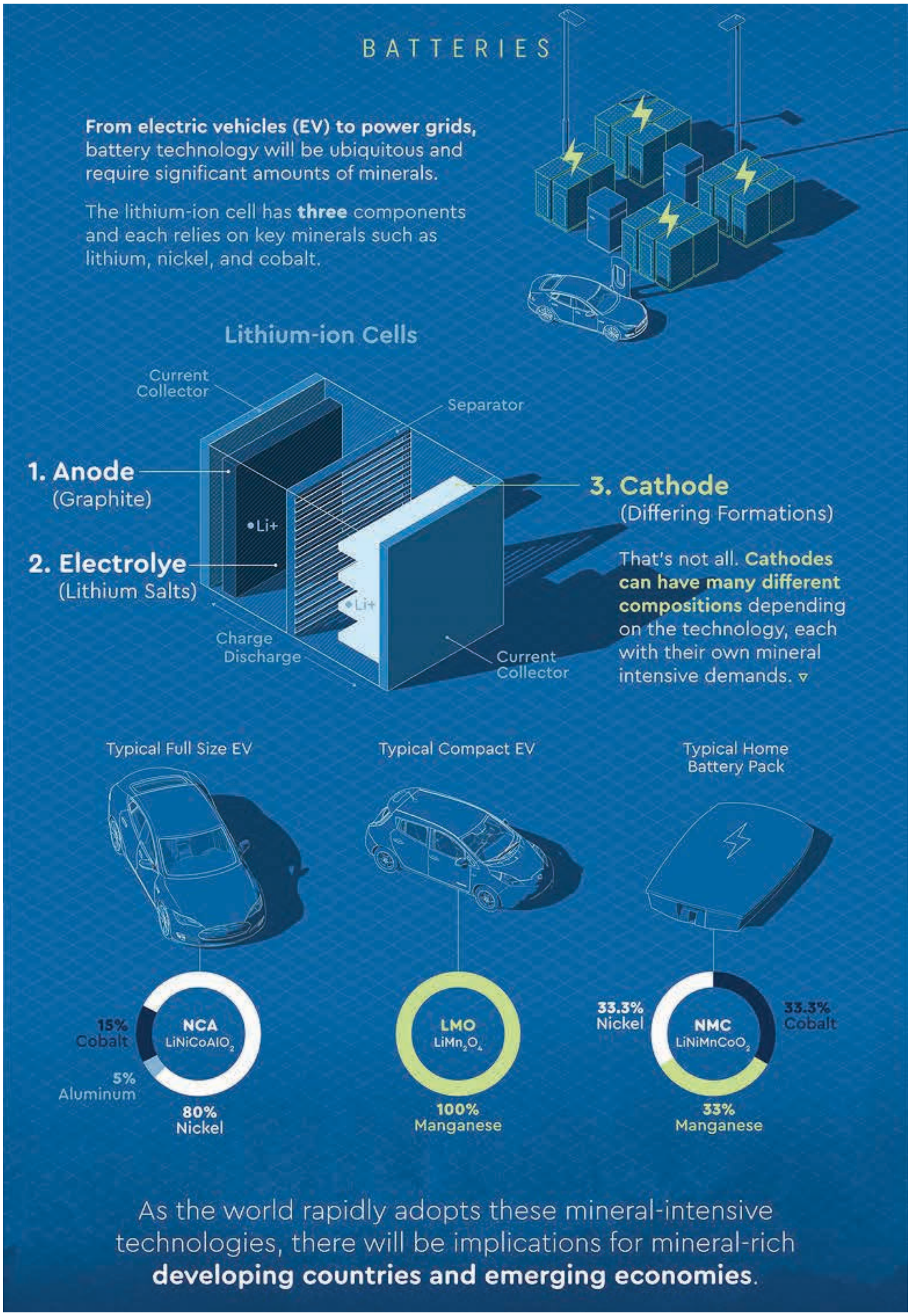
Beyond the family of Li-ion batteries, Table 1.3 outlines the contending technologies for future reuse/recycling.

In terms of recycling and reuse, although flow batteries are regarded as one of the more serious rivals to the Li-ion battery their prospects pale when viewed through an economic lens. The Li-ion battery is predicted to enjoy US$107 billion of investment by 2024 compared to a US$300 million for all flow batteries by 2025. Such investments have already created a lower price for Li-ion, which has made it more competitive.

Battery pack prices for electric vehicles are typically set according to cost per kilowatt hour. Over the last 10 years prices have fallen as production has burgeoned. As Figure 1.2 shows, they now cost around US $156 per kilowatt hour, according to Bloomberg NEF, representing an 85% decline from the approximate cost in 2010 of US$1,100/kWh. Continued production and improving efficiencies are set to push prices below US$100/kWh by 2024. It is worth noting that 2024 is the year when electric vehicles manufacturers predict that their output will reach price parity with internal combustion engine vehicles.

The rapid growth in the EV and Li-ion battery market underscores the urgent need for a secure plan for the full life cycle of these products, especially successful exploitation of the technology beyond its first life (first discrete phase of use).

FIGURE 1.1: Battery Technologies



Note: Infographic *available* for download at: https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action.

TABLE 1.1: **Positive Electrode Options (mostly used in electric vehicle applications)**

Technology	Company	Target Application	Date	Benefit
Lithium Nickel Manganese Cobalt Oxide (NMC) $LiNi_xMn_yCo_zO_2$ [a, b, c]	Imara Corporation, Nissan Motor, Microvast Inc., LG Chem	Electric vehicles, power tools, grid energy storage	2008	good specific energy and specific power density
Lithium Nickel Cobalt Aluminium Oxide (NCA) $LiNiCoAlO_2$ [d, e,f]	Panasonic, Saft Groupe S.A., Samsung	Electric vehicles	1999	High specific energy, good life span
Lithium Manganese Oxide (LMO) $LiMn_2O_{4h,}$ [g, h, I, j]	LG Chem, NEC, Samsung, Hitachi, Nissan/AESC, EnerDel	Hybrid electric vehicle, cell phone, laptop	1996	
Lithium Iron Phosphate (LFP) $LiFePO_4$ [k, l, m, n]	University of Texas/ Hydro Quebec, Phostech Lithium Inc. Valence Technology, A123Systems/MIT	Segway Personal Transporter, power tools, aviation products, automotive hybrid systems, plug-in hybrid electric vehicle (PHEV) conversions	1996	Moderate density (2 A·h outputs 70 amperes); High safety compared to Cobalt / Manganese systems; Operating temperature >60°C (140°F)
Lithium Cobalt Oxide (LCO) $LiCoO_2$ [o]	Sony	broad use laptop (first commercial production)	1991	High specific energy

Note: Tables and citations from Wikipedia website on Lithium-ion Batteries.

a. *Imara Corporation Website, July 2009.*

b. *O'Dell, John Fledgling Battery Company Says Its Technology Boosts Hybrid Battery Performance Green Car Advisor; Edmunds Inc, (17 December 2008).*

c. *LeVine, Steve (27 August 2015). Tesla's coattails are carrying along Panasonic, but a battle for battery supremacy is brewing. Quartz. Retrieved 19 June 2017.*

d. *Blomgren, George E. (2016). The Development and Future of Lithium-ion Batteries. Journal of the Electrochemical Society. 164:* A5019–A5025. doi:10.1149/2.0251701jes

e. *Samsung INR18650-30Q datasheet (PDF).*

f. *Jost, Kevin [ed.] Tech Briefs:* CPI takes new direction on Li-ion batteries (PDF). aeionline.org; Automotive Engineering Online. October 2006.

g. *Voelcker, John; Lithium Batteries Take to the Road, Archived IEEE Spectrum. September, 2007.*

h. *Loveday, Eric. Hitachi develops new manganese cathode, could double life of Li-ion batteries. www.autoblog.com, April 2010.*

i. *Nikkei:* Report: Nissan On Track with Nickel Manganese Cobalt Li-ion Cell for Deployment in 2015 Green Car Congress (blog). November, 2009.

j. *EnerDel Technical Presentation (PDF). EnerDel Corporation. October 2007.*

k. *Elder, Robert and Zehr, Valence sued over UT patent, Austin American-Statesman, Feb, 2006.*

l. *Bulkeley, William M. "New Type of Battery Offers Voltage Aplenty, at a Premium". The Day. p. E6, Wall Street Journal, November 2005.*

m. *A123Systems Launches New Higher-Power, Faster Recharging Li-Ion Battery Systems Green Car Congress; A123Systems (Press release). November, 2005.*

n. *Hayner, CM; Zhao, X; Kung, HH "Materials for Rechargeable Lithium-Ion Batteries". Annual Review of Chemical and Biomolecular Engineering. 3 (1):* 445–471. doi:10.1146/annurev-chembioeng-062011-081024. PMID 22524506.; January 2012.

o. *"Lithium-ion technical handbook" (PDF). Gold Peak Industries Ltd. November 2003.*

RECYCLING AND REUSE OF LIBESS

Clearly batteries must be a key element of climate action if the global Paris Climate Agreement target is to be attained. What is also clear is that recycling and reusing Li-ion batteries will be a critical component in helping developing countries make a rapid and sustainable transition in delivering clean energy. If recycling and reuse practices are properly introduced at scale, greenhouse gas (GHG) emissions and costs should both be mitigated.

For the purposes of this report, recycling and reuse are defined as two distinct activities (though sometimes discussed in tandem). Recycling refers to the retrieval of specific elements in a produced technology for subsequent use in other technologies, perhaps, including other batteries. By contrast, reuse (or repurposing) refers to putting the battery technology as a whole

TABLE 1.2: **Negative Electrode Options (mostly used in smaller, appliance-based applications)**

Technology	Density	Company	Target Application	Date	Comments
Graphite[a]		Targray	The dominant negative electrode material used in lithium-ion batteries.	1991	Low cost and good energy density. Graphite anodes can accommodate one lithium atom for every six carbon atoms. Charging rate is governed by the shape of the long, thin graphene sheets. While charging, the lithium ions must travel to the outer edges of the graphene sheet before coming to rest (intercalating) between the sheets. The circuitous route takes so long that they encounter congestion around those edges.
Lithium Titanate (LTO) $Li_4Ti_5O_{12}$[b, c]		Toshiba, Altairna	Automotive (Phoenix Motorcars), electrical grid (PJM Interconnection Regional Transmission Organization control area, US Department of Defense	2008	Improved output, charging time, durability, safety, operating temperature
Hard Carbon[d]		Energ2	Home electronics	2013	Greater storage capacity
Tin/Cobalt Alloy		Sony	Consumer electronics (Sony Nexelion battery)	2005	Larger capacity than a cell with graphite (3.5Ah 18650-type battery)
Silicon/ Carbon[e]	Volumetric: 580 W·h/l	Amprius	Smartphones, providing 5000 mA·h capacity	2013	Uses < 10wt% Silicon nanowires combined with graphite and binders. Energy density: ~74 mAh/g Another approach used carbon-coated 15 nm thick crystal silicon flakes. The tested half-cell achieved 1.2 Ah/g over 800 cycles.

a. Northwestern researchers advance Li-ion batteries with graphene-silicon sandwich; Solid State Technology. *Electroiq.com. Zhao, X.; Hayner, C. M.; Kung, M. C.; Kung, H. H. (2011). In-Plane Vacancy-Enabled High-Power Si-Graphene Composite Electrode for Lithium-Ion Batteries. Advanced Energy Materials. 1 (6): 1079–1084.* doi:10.1002/aenm.201100426. *November 2011.*

b. Acceptance of the First Grid-Scale, Battery Energy Storage System *(Press release). Altair Nanotechnologies. 21 November 2008.*

c. Gotcher, Alan J. Altair EDTA Presentation*(PDF). Altairnano.com. Archived from* the original *(PDF) November, 2006.*

d. Synthetic Carbon Negative electrode Boosts Battery Capacity 30 Percent; MIT Technology Review. *Technologyreview.com (2 April 2013). Retrieved 16 April 2013.*

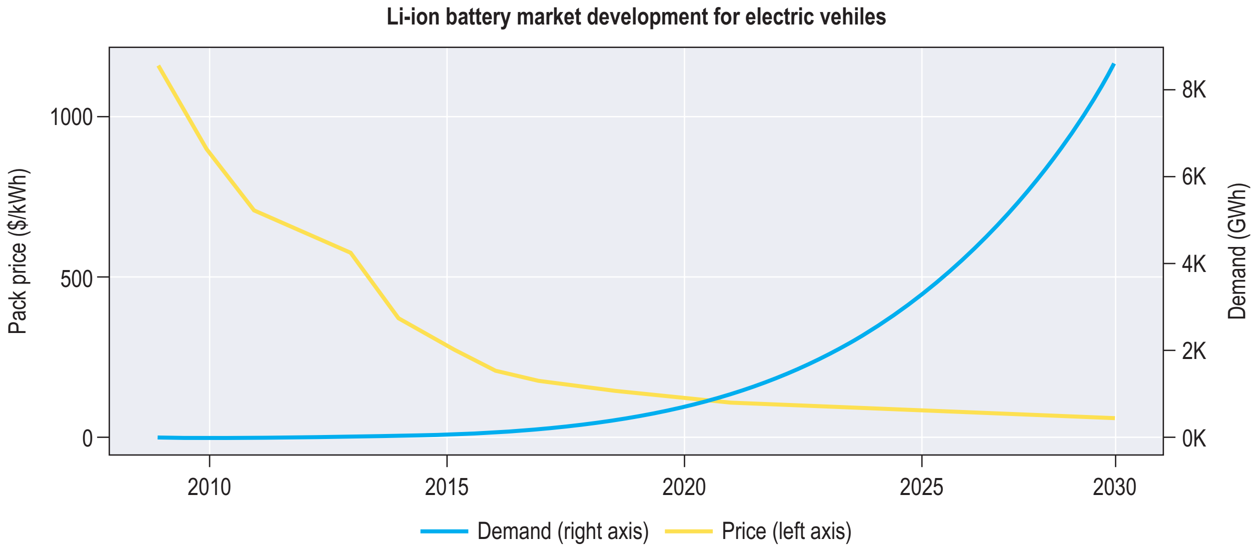
e. Newman, Jared, Amprius Begins Shipping a Better Smartphone Battery May, 2013.

to a second use that is quite distinct from its primary production purpose; for example, transitioning a Li-ion battery from an EV to providing power, or backup power, as a stationary energy provider (see Chapter 2 for more details on reuse).

The overriding benefit of batteries—particularly for isolated communities and economic activities—is that it supplants costly, inefficient, environmentally harmful fossil fuel operations, such as diesel generators. Nevertheless, Li-ion batteries have their own set of sustainability challenges. For example, it is recognized that simply increasing production of batteries exclusively through primary extraction and manufacturing processes will bring their own set of issues, such as the consequences of increasing extraction activities in eco-vulnerable areas. The challenge is not only how to dramatically raise the profile and use of batteries in the new energy future (Hayner, Zhao, and Kung 2012), but also how to produce these batteries with sustainability features, taking into account environmental, economic, technical, and social circumstances.

Although lead batteries, in their primary form, are ceding their role to Li-ion batteries in such technologies as electric motor vehicles, they continue to enjoy success with respect to recycling. Indeed, the story of recycling and reuse of lead batteries is one of unparalleled success (at least in the developed world). Estimates of 90% or more of lead batteries are recycled

FIGURE 1.2: The Market Growth of the Li-ion Battery



Source: Rocky Mountain Institute/BloombeeryNEF. Data is projected starting in 2020.

TABLE 1.3: **Alternatives to Li-ion Batteries**

Commercial Alternatives to Li-ion	Future Competitors to Li-ion Batteries
Flow Batteries (most robust competitor): projected to have a CAPEX of US$370 million in 2025, compared to over US$1 billion for Li-ion batteries. Also covers Iron Chrome, Vanadium, and Zinc Bromide.	**Solid State:** offer higher energy density, safety, and faster recharge. A challenge is that during charge and discharge dendrites form, reducing coulombic efficiency. Probably the most significant competitor to LiBESS, the question remains whether solid-state will be commercially competitive to the second generation of EV Li-ion batteries.
Nickel Zinc Batteries: the advantage of the NiZn battery is higher energy density relative to cost. It is targeting specific applications, including data center rack-based uninterruptible power supply (UPS) and power management.	**Li-S:** rechargeable battery noted for its high specific energy. It may succeed Li-ion due to high energy density and lower cost (use of sulfur). The issue limiting commercialization is the polysulfide “shuttle effect,” which results in leakage of active material from the cathode resulting in low cycle life.
Nickel Metal Hydride: rechargeable battery whose energy density can approach that of Li-ion. Used widely in hybrid electric vehicle (HEV) applications from 1999-2019. It has now been superseded by the Li-ion battery in almost all HEV and EV applications. Its low internal resistance is advantageous in high current applications.	**Li Air:** metal air battery chemistry that uses oxidation of lithium at the anode and reduction of oxygen at the cathode to induce current flow. Focused on the EV market because of the high theoretical energy density (10 times greater than Li-ion) but problems include recharging time, water and nitrogen sensitivity, intrinsically poor conductivity, and pure lithium metal createss safety issues. Despite huge potential returns, those challenges have caused many companies and researchers to abandon this chemistry.
Zinc Air: metal air electrochemical cell technology, these batteries have the potential to be energy dense (up to three times the energy density of Li-ion) but also show problems with electrolyte management, dendrite, and charging issues.	**Ultra-capacitors:** lightweight, faster to charge, safer, and composed of non-toxic materials such as carbon. Motive power applications drive exploration of this technology. If it could store more energy and still retain the features it exhibits now, then it could challenge Li-ion.

Sources: Recharge; The Battery Report (April 2018); HE Melin, The Li Ion battery End of Life Market 2018-2025; David Coffin and Jeff Horowitz, The Supply Chain for Electric Vehicle Batteries; US ITC- Journal of International Commerce and Economics, December 2018 and Shane Thompson; battery recycling industry expert.

globally, making it the predominant recycled consumer product.[4] There are several reasons for this: (i) all battery manufacturers consistently use the same materials and design in their product, so the recycling process is comparatively simple; (ii) it is profitable—disassembly from these products is cheaper than primary extraction activities (disassembly is automated for lead batteries, whereas for Li-ion batteries it is a manual exercise); and (iii) there are strict rules that govern the disposal of lead batteries due to the toxicity of its key component, lead.

Lessons learned from lead battery life cycle that could translate into the same sort of success for Li-ion batteries include the following:

- The same network responsible for the distribution of lead-based batteries is also responsible for the safe collection of spent batteries, which are used almost entirely towards the construction of new batteries.
- The similarity in the components and design of lead batteries makes it economical to produce replicable models.
- Other profitable uses have been found for lead battery components (the overall chemical make-up of lead batteries being relatively simple). Interestingly, Chinese experience has shown that low-speed electric vehicles with manually detachable batteries can, to an extent, make use of the lead-acid battery network.
- The main recycled component—lead—is known to be of high quality, so it is purchased in a recycled form without hesitation.
- There are strict regulations regarding the disposal of batteries—most governments have imposed regulations that make recycling mandatory.

Like the relative success story with respect to lead acid batteries, it is hoped that the recycling and reuse of Li-ion batteries can serve as a means to help their economies grow in a socially and environmentally responsible manner. However, currently the regulatory and standards based regime around Li-ion batteries is weak and inconsistently applied[5], nor are the objectives, which typically work to limit the trading of hazardous goods, in line with a robust future EOL global regime developed for LiBESS.

Delivering LiBESS in a sustainable manner can help developing countries to adopt clean energy technologies. The recycling and reuse of Li-ion batteries can serve as a means to help their economies grow in a socially and environmentally responsible manner.

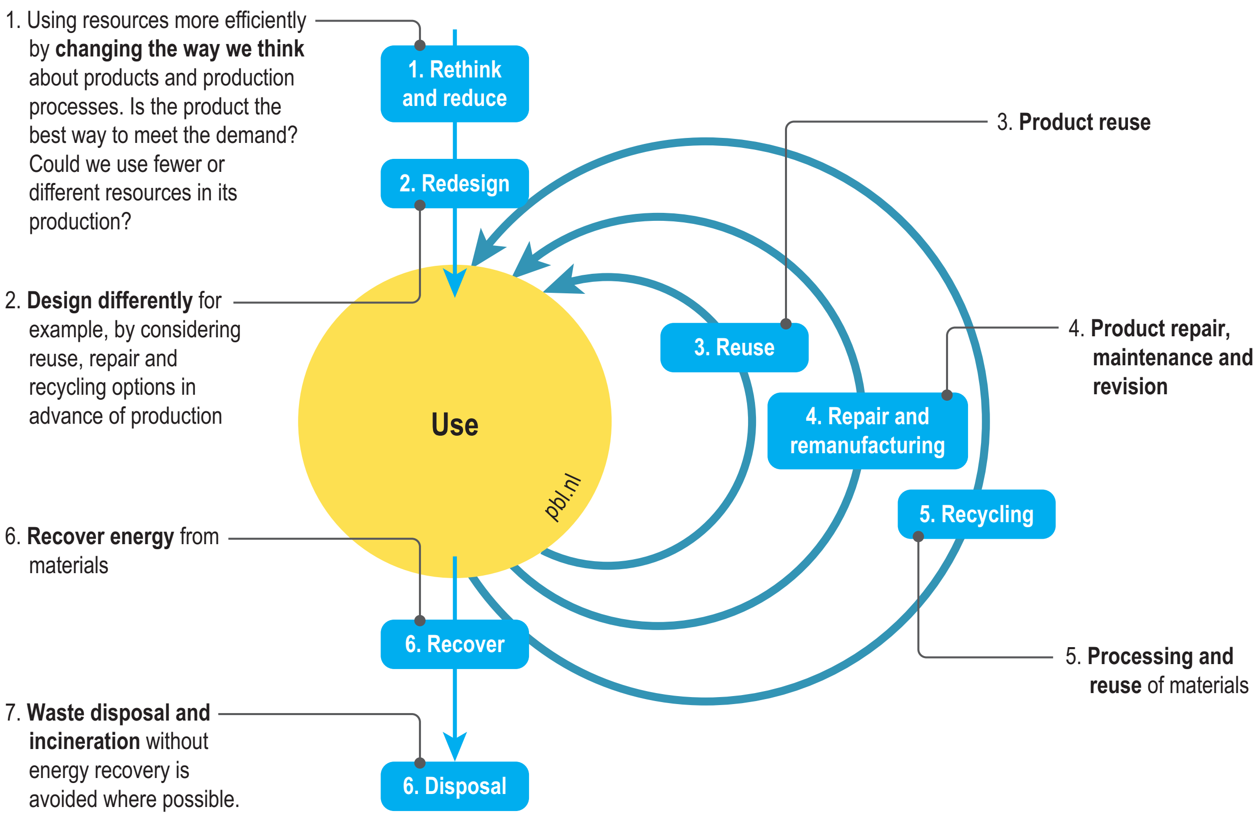
Such an approach will be developed in the context of a ‘circular economy’ or ‘end-of-life’ approach. The concept of a circular economy is relatively simple: it recognizes that an exclusive focus on economic growth does have its limits, particularly from an environmental perspective. Thus, it seeks to “remove waste and pollution by making sustainable products and materials that do not have built in obsolescence and their creation does not exceed the limits of the environment or natural systems.”[6]

It is increasingly urgent that the design of LiBESS batteries should take end-of-life management into account, extending the lifetime of products and materials as long as possible—for both primary and secondary purposes. Disposal should be avoided to the extent possible, with hazardous materials kept on a recycle/reuse mode, ideally, in perpetuity. It is the poorer countries that are victimized by illegal and unsustainable disposal practices: a full life cycle approach for LiBESS is fundamental in ensuring that its products do not add to the hazardous waste crisis. Figure 1.3 encapsulates the concept of a circular economy.

A circular economy approach—one that takes into account what happens to batteries once their primary purpose has been expended—should not represent a compromise with respect to the attainment of environmental or economic goals. In that respect, recent reports by the World Economic Forum Global Battery Alliance (GBA) estimate that moving from a linear to a circular economy approach could result in a reduction of 34 Mt in GHG emissions while creating an additional economic value of approximately US$35 billion (GBA 2020, p. 7). This would be realized through decreasing reliance on extraction and processing of primary materials, and an increasing reliance on recycling and repurposing practices. Or put another way, simply repurposing or reusing EV batteries to becoming power providers could lower the costs of EV charging infrastructure by 90% by 2030 while supplying 65% of stationary battery power grids (GBA 2019, p. 7). What is not clear in these projections by the GBA and IRENA is the extent of developing country engagement behind these numbers—certainly at this point, the penetration of EVs in most developing countries is minimal (with the exception of China). For example, the total number of EVs in South Africa as at Oct 2019, is only 1,000 out of the total of 12 million registered cars (Kuhudzai 2020).

It should be understood that a circular battery value chain could be a major near-term driver of efforts to realize the 2°C Paris Climate Agreement goal in the

FIGURE 1.3: The Circular Economy: A Pictorial Depiction



Source: The Netherlands Environmental Agency; Opportunities for a Circular Economy; https://themasites.pbl.nl/o/circular-economy/

transport and power sectors. Recycling and reuse practices should also further developing countries' environmental, economic and energy security goals: environmental, at the very least, to the extent that this will mitigate early and unsustainable disposal of Li-ion batteries; economic, in that it will significantly make good the costs of Li-ion battery manufacturing and hence make them more affordable for use in developing countries (it has been estimated that reused batteries will be 30–70% less expensive than new counterparts by 2025[7] and could provide as much as 26 GWh of power by that same year[8]); and, security to the extent that it will shield a country's exchequer from the cost of importing fossil fuels for power, while conserving valuable resources.

Notwithstanding the current market position of Asian, Western European, and U.S. interests that dominate the current recycling/reuse market for Li-ion batteries, the question is not if, but how can we work to ensure that developing countries become equal contributors in a circular economy?[9] A second-life approach for LiBESS would mean transforming its primary function as the power source for EVs to providing a range of stationary power provisions: from providing direct energy services at the micro grid/individual home level to backing up wind or solar energy power supplies. Typically, an EV Li-ion battery can operate satisfactorily in a vehicle at up to 80% capacity for roughly 10 years before its performance is compromised. It can then be successfully reused as a stationary source and offer a range of additional services. For instance, it can provide electric vehicle support to mini grids—the former extending the life span of the LiBESS by 30 years and the latter by six years (Casals et al. 2018), assuming the products have been correctly refurbished and tested.

Ambrose et al. (2014) argue that if properly planned, repurposed batteries could "become the storage hubs for community-scale grids in the developing world" (p. 1), estimating that a focus on mini grids in local communities in developing countries, will see repurposed batteries providing power to over 35 million homes currently without such access (p. 5). Action to promote the wide use of second-life Li-ion batteries will serve to diversify and increase the resilience of local power sourcing, lead to increased effective backup power, and expand the market for wind and solar power (Taljegard et al. 2019).

It should also be noted that while a circular economy approach is key to achieving a sustainable future, this does not mean that there will be no need to continue to mine and process primary minerals and metals for future clean energy technology. There is simply not enough lithium or other key metals being recycled to meet global climate targets.[10] In addition, extending LiBESS beyond its initial transportation function to cover stationary sources (reuse rather than recycle), may result in an increase in primary extraction to cover EV battery demands. Resource-rich developing countries could be well positioned to provide those resources. Thus, the approach cannot be regarded as a 'zero-sum' situation. There is no binary choice between extraction or recycling/reuse—on the contrary, both are needed.

A circular economy approach for LiBESS in developing countries is relatively unresearched and untested but it holds great environmental and economic promise for all countries. Most of the research and implementation in the field of batteries, particularly with respect to recycling and reuse options, is emanating from a few countries—especially China and South Korea. In addition, the European Union, the United Kingdom, and the United States have all recently embarked on ambitious programs intended to integrate battery technologies with a circular economy approach in mind, focusing on modalities for recycling and reuse.

Other developing countries run the risk of falling behind in the global economy of recycled/repurposed storage batteries. What areas of recycling and reuse best suit developing countries? As consumers of the growing LiBESS market? To secure more critical minerals and metals for their own economic development? Each developing country will need to make its own choices, based on the issues discussed below.

TECHNOLOGY ATTRIBUTES OF RECYCLING AND/OR REUSING FOR LIBESS

In discussing a circular economy approach to energy storage batteries, what are the technology attributes of LiBESS most relevant for environmental sustainability? There is little doubt that these must focus on developing effective recycling/reuse systems.[11] They should work to emphasize the economic and environmental benefits of putting batteries to market that are purposed to extend their first life to the extent possible, and then develop design features suited to reuse and recycling. Business models must also clarify ownership and responsibilities for first-life Li-ion batteries over the full value cycle of their use. Without the right business model, it is simply not possible to design products that are easily reused or recycled, or to have an effective system for reclaiming and rechanneling products into alternative uses.

Typically, much attention is paid to the minerals that go into the batteries. For example, cobalt comprises an essential component of the majority of Li-ion batteries. This has garnered considerable negative attention in view of human rights violations, particularly in the Democratic Republic of Congo (DRC). These are deep and valid concerns, but they need not obscure consideration of other key elements in a full value chain approach to Li-ion batteries—particularly when seeking more effective means to develop robust reuse and/or recycling of Li-ion batteries in developing countries.

In that respect, an end-of-life (EOL) strategy for developing countries that begins to implement the use of Li-ion batteries in their grid system could be a very exciting opportunity to both reduce GHG emissions and costs. The Faraday Institution and its ReLiB project has been extremely informative in this context. Its aim is "to establish the technological, economic and legal infrastructure to make the recycling of close to 100% of the materials contained in Li-ion batteries from the automotive sector possible."[12] Key areas to consider when identifying relevant technology attributes for the purposes of reuse and recycling in LiBESS include (Yongchong, Liu, and Liu 2019):

- **Nature of materials used:** LiBESS should, to the extent possible, be "self-consistent" or demonstrate resilient integrity. It is important that materials are not introduced during the manufacturing process that may cause contamination.
- **Initial design and structure:**[13] development of LiBESS should consider prolonging Li-ion battery life include its charging speed, depth of discharge, loading, and exposure to extreme temperatures. Specific checks would cover what causes capacity loss, how rising internal resistance affects performance, impacts of elevated self-discharge, and determination of the lowest capacity at which the

battery can still be discharged. Critical to achieving this is designing a Li-ion battery that effectively addresses key sensitivities, including a technological and implementation framework that balances health and safety with recycling/reuse considerations.

- **Structure of LiBESS:** relative complexity of disassembly; standardized protocols for LiBESS, accounting for health and safety considerations. The industry should work towards developing LiBESS that is as standardized as possible, particularly with respect to disassembly practices.[14]
- **Access to key ingredients:** extending life of first batteries and ensuring an easy transition to reusing or recycling products. In the case of recycling, the product should be able to be disassembled easily and safely; in the case of reuse, the product should be amenable to minimal resetting of battery packs.
- **Recovery:** Continue innovation in recovering valuable materials which should also ease production of second-life batteries.
- **Disposal:** governments will need to put in place decommissioning regimes to be incorporated in the design of LiBESS (US Energy Storage Association 2020, p. 6-7).
- **Collection practices:** enhancing incentives to develop a robust recycling/reuse market in developing countries.
- **Full life cycle accounting:** relative GHG footprint of energy storage batteries, including under recycling and reuse regimes.

NOTES

1. Material provided from announcement on launch of Energy Storage Partnership in May, 2019 in Vancouver. See https://www.worldbank.org/en/news/press-release/2019/05/28/new-international-partnership-established-to-increase-the-use-of-energy-storage-in-developing-countries
2. Alarco and Talbot (2015).
3. See Table 1.3 for the technical challenges that still beset solid-state batteries
4. The Global Battery Alliance estimates that 30% of GHG reductions required to meet global targets by 2030 will need to be met through the deployment of Energy Storage Batteries. It will only need to dramatically grow beyond that mark post 2030. (See GBA 2019).
5. Chapter 3 for overview on country/region actions to address Li-ion batteries
6. Part of the reason for the high attention being paid to recycling lead batteries relates to its high toxicity levels (Gaines 2014, p. 3).
7. See Engel, Hertzke, and Siccardo (2019).
8. See Martinez-Lacerna (2018).
9. For description of scope of issue, see Jacoby (2019).
10. See WBG report “Climate Action Minerals”: Still in publication. Also see GIZ presentation : Mineral Sourcing for Electric Vehicle Batteries : Insights into Raw Material Extraction and Governance which estimates 30% of battery storage needs could be met through recycling, March 19, 2020
11. See the Global Battery Alliance’s “Battery Passport” initiative as a tool for promoting a circular economy approach with respect to batteries: https://www.mining.com/battery-passport-guiding-principles-on-value-chain-data-launched-at-world-economic-forum/
12. See the following reports from The Faraday Institution: https://relib.org.uk/ and https://faraday.ac.uk/research/lithium-ion/recycle-reuse/
13. See “How to prolong lithium based batteries” https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries.
14. Personal email from Hao Liu, Yongchong Chen & Dandan Liu.

2 CURRENT REUSE AND RECYCLING PRACTICES

RECYCLING AND REUSE: SOME COMMON ISSUES

One of the first challenges that developing countries[1] face when attempting to develop a circular economy perspective on LiBESS is how to develop a robust system for recycling/reuse when the current deployment of Li-ion batteries is as low as it is. While there is no doubt about the strong growth of electric vehicles (EV) in the global transportation marketplace, these still represent fewer than 10% of road vehicles in most countries. As virtually all reused or recycled batteries will find their initial purpose in powering road vehicles, there is a dearth of data and evidence on the second life of Li-ion vehicular batteries as energy storage batteries (ESBs). Figure 2.1 provides a relatively basic overview of the structure of an efficient EV battery management system:

To achieve a high use of batteries removed from EVs, it is critical to ensure that these are collected efficiently and do not 'leak' from the system. If the regulatory system does not ensure that the collection system operates efficiently, it will be impossible to monitor the fate of end-of-life EV batteries.

There are currently a handful of private sector firms that focus globally on the collection of Li-ion batteries for the purpose of recycling/reuse. None of these have a significant presence in developing countries outside of China and India. Currently, this handful of private firms that devote their full attention to recycling Li-ion batteries include: Umicore (Belgium), Retriev Technology (USA), American Manganese (Canada), and Accurec and Redux Recycling (Manhart et al. 2018, p. 20). Recycling firms active in Asia include: CALB (China), Earthtech (Korea), and Sumitomo Metals (Japan). When first implementing electric battery capacity in developing countries, an important design consideration is the availability (if any) of regional collection centers linked to a network of local 'extraction' centers.

DATA AND SKILLS

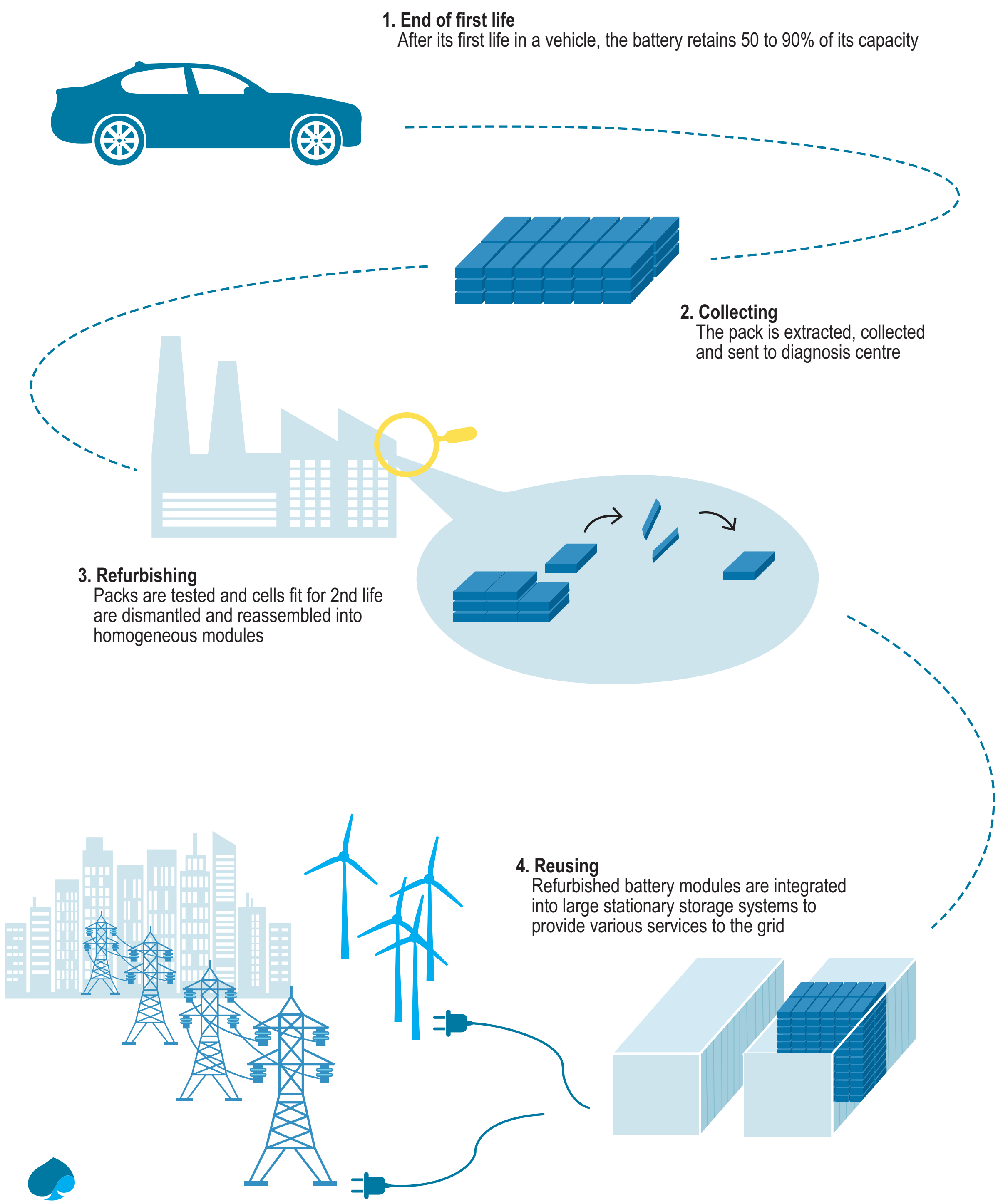
In developed and developing countries alike, there is a lack of data and skills. Skills such as triaging, battery manufacturing, servicing of batteries, dismantling, and recycling are requisite for functional systems. Currently the resources are lacking, due to a number of factors, not the least of which is inadequate compensation for the level of engineering expertise required as well as inadequate recognition of the risks to workers in these installations (Jacoby 2019. p. 3).

RECYCLING VS. REUSING

Another area of consideration relates to the respective challenges and opportunities of recycling and reuse or repurposing of Li-ion batteries. Simple waste mitigation models typically categorize reuse practices as more sustainable than recycling as the operations related to disassembly, transportation, and redeployment should be much simpler, and hence more environmentally benign. In addition, as briefly alluded to above, recycling processes for industrial Li-ion batteries remain immature and it has been contended that their attendant economic complexities continue to defy any easy resolution. Given the current expenses related to disassembly, transportation, and storage of discrete materials, any attempts to lower costs on primary assembly of batteries will only make recycling less financially attractive (Capgemini 2019; Harper et al. 2019). Indeed,

FIGURE 2.1: The Second Life Battery Cycle

The second life battery cycle: after about 10 years in a vehicle, lithium-ion batteries can be reused for another purpose and thereby begin a "second life"



Source: Capgemini. 2019, April.

the question can reasonably be posed as to whether a business case can be made for recycling in the absence of additional regulations to support the industry.

However, there are also questions about the overall effectiveness and attraction of simple reuse practices. Currently, the reuse of batteries is only economic if it becomes possible to reuse them with minimal disassembly. However, given that there is little consistency between manufacturers of current Li-ion batteries (unlike lead batteries), each facility would need its own reuse applications. At present, no single model is sufficiently prominent to justify such an approach,[2] though a more homogenous set of designs for EV batteries can reasonably be expected in future.

Despite the challenges facing recycling and reusing, it is clear that both of these practices, if we look to lead-acid batteries as a precedent, could be well positioned to grow over the next few decades. It is not a matter of mining versus recycling/reusing, or recycling versus reusing, rather it is a prospect of 'yes to all'. Challenges that face the Li-ion repurposing agenda include:

- the wide range of Li-ion batteries being manufactured, with few standardized features/regulations in place governing recycling and reuse practices and technologies, rendering disassembly and reassembly operations costly and potentially hazardous;
- the continued decrease in prices of new batteries;
- lack of standards regarding the performance level of batteries; and,
- no regulatory regime in place with respect to the repurposing and/or disposal of Li-ion batteries with the exception of China and Europe (Engel, Hertzke, and Siccardo 2019, p. 3).

RECYCLE

The most prominent challenges with respect to the current recycling of Li-ion batteries relates to "technical constraints, economic barriers, logistic issues and regulatory gaps" (Jacoby 2019, p. 2). At present, while there is an impressive breadth of research growing around this issue, actual recycling rates are assumed to be quite low at this point. Technical constraints typically involve the complexity of Li-ion battery disassembly (by contrast with the relatively straightforward disassembly of lead battery products).

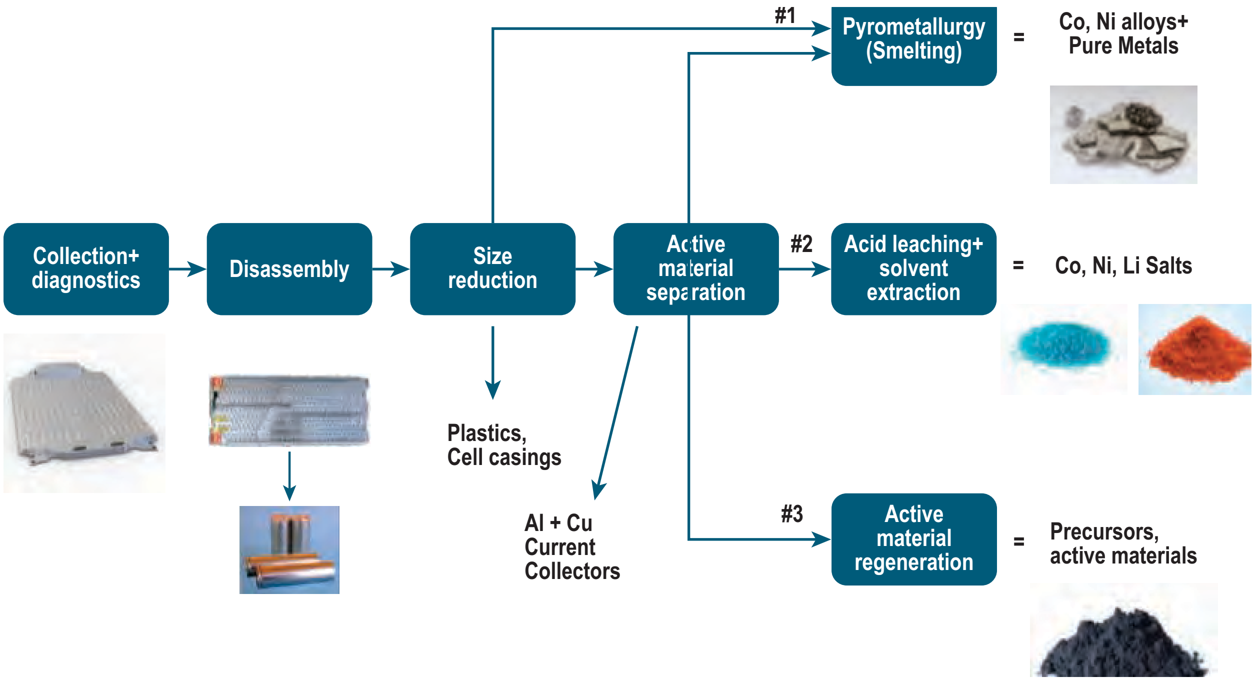
The recycling of Li-ion batteries is characterized by a number of challenges: economic, technical, logistical, and regulatory (Gaines 2014). The economic challenge is that, with the exception of cobalt and nickel, most of the other constituent materials are more costly to salvage than simply to mine directly.[3] Figure 2.2 outlines the recovery of the various constituents. The technical challenge involves the existence of many different types of Li-ion batteries, each with its own distinct design and component features, making it difficult to establish recycling centers that could cope with the full range of Li-ion batteries currently in use.

Li-ion batteries intended for EVs and back up power sources are typically much larger than lead batteries, with increasingly voluminous battery packs, making disassembly more complex and potentially riskier. They are also typically built into their applications and are not designed to be separated by the user (Melin 2019, p. 10). Products with Li-ion batteries (such as cell phones and EVs) are typically returned to recyclers of phones and cars, not dedicated reyclers of batteries. Logistical challenges relate to collection and transportation—there are no standard guidelines that govern the collection and storage of Li-ion batteries, nor, with the exception of a handful of countries, are there any public regulations regarding the discrete recycling of large format Li-ion batteries (Melin 2019, p. 4). Although much can be learned from the precedent set by lead-acid batteries, Li-ion batteries clearly present a unique set of challenges.

Despite such challenges, the benefits of recycling cannot be overlooked. If production of Li-ion batteries proceeds at the rate widely predicted, materials that can be extracted and recycled from these batteries will become economically profitable in time. At scale, recovered cobalt, nickel, manganese, and lithium products (among others) will contain higher concentrations of the element than found in natural ores (Jacoby 2019, p.4). Over the near term, recycling lithium iron phosphate is expected to play an increasingly critical role in EV and large-scale energy storage—it is the only product currently providing an economic incentive for recycling. Thus, technology that utilizes directly recycled materials, such as lithium ion phosphate, should be promoted.[4]

Li-ion battery recycling practices are in a state of evolution. Smelting (pyrometallurgy) is a relatively capital-intensive approach (producing significant GHG emissions) in extracting/recycling some critical relevant materials—cobalt, nickel and copper—but not other key elements, such as lithium or aluminium, especially from an economic perspective.[5] Hydrometallurgy processing—chemical leaching—is much less energy

FIGURE 2.2: Recycling Steps for LiBESS



Source: Adapted from Evan (2018).

intensive in its operations and can capture a wider harvest of recyclable materials than smelting. However, the management of the caustic reagents needed for leaching entails technical challenges. Research is ongoing: for example the US Department of Energy's research group, ReCell, is investigating the so-called "direct recycling" process which uses supercritical carbon dioxide (sCO_2) as an agent for removing the electrolyte and then physically crushing the cell on the basis of density differences.[6] This latter process appears to be the most environmentally benign. It can theoretically capture/recycle all key components in Li-ion batteries and does not require environmentally harmful caustic agents. Furthermore, it consumes only a small fraction of the energy required for pyrometallurgy.

Research around the recycling of Li-ion batteries has been markedly more active than on reuse opportunities and practices. The vast majority of peer reviewed articles on the topic originate from China and South Korea. Both countries saw it as a strategic investment decision, working to enhance their 'critical metals' security in view of the growing EV and electronics market (Melin 2019, p. 27). The prevalence of Asian countries' research in this area is entirely consistent with the predominance of Li-ion batteries in their manufacturing profile. China, South Korea, and Japan together account for over 90% of all Li-ion battery production worldwide.

REUSE[7]

The largest portion of research on reuse (in contradistinction to recycling) has been academic, typically as part of larger industrial projects. Research around reuse has been mainly the purview of European and US institutions, although China has also contributed. Compared to recycling, reuse is still largely unexplored territory, from a practical research perspective.

One of the areas most often examined in research is the extent to which batteries could profitably be used to support power generation and backup activities (off grid and backup for power in rural contexts or in developing countries) where it would be uneconomic for new energy storage batteries.[8] Other studies appear to confirm the contention that reuse is a profitable and affordable venture for more marginal user groups (rural and less developed countries). However, this is a rapidly changing scenario—as costs associated with the manufacture of new Li-ion batteries continue to fall, the economic incentive to reuse becomes less compelling (Melin 2019, p. 26).

The relative environmental benefits of reuse are recognized in the literature. They are significant in a number of respects—by supplanting diesel or gas powered plants as a backup to renewables such as wind or solar, and by exerting considerably lower environmental impacts (in terms of GHG emissions, energy expended and local environmental contaminants) than alternative recycling options. It even makes a difference when compared to the GHG emissions associated with building new batteries: one report estimates that GHG emissions associated with the life cycle of a used Li-ion battery are 25% fewer than a unit powered by a new battery (Engel, Hertzke, and Siccardo 2019, p. 72).

The size of the potential market for second-life batteries is estimated to be the product of four variables: sales of EVs; type of battery; customers' behavior with respect to battery upgrades; and, the percentage of reused batteries that actually make it to the marketplace.[9] Based on these variables, Reid et al. (2016) estimate that reused or secondary batteries could provide up to 1,000 GWh globally. This growth could be compromised by a number of factors, including:

- **Market for energy storage applications**: whether future regulations and public policies help or hinder the development and uptake of energy storage batteries as new batteries and relevant materials become less expensive to produce—and the risk that the case for reuse strategies becomes less compelling (Casals and Garcia 2016)
- **Cheaper options:** the cheaper the manufacturing costs of first-life Li-ion batteries, the more constrained are the profits promised by second-life batteries (Casals and Garcia 2016)
- **Reuse cost:** the cost of 'repurposing' is competitive
- **Data:** a lack of comprehensive data and basic research on the longevity/second-life potential of Li-ion batteries

Specific choices and opportunities for developing countries with respect to the second life of LiBESS will largely be determined by local circumstances. It is important at the outset to consider whether second-life applications can be effective, efficient, and safe in locations with very high or very low ambient temperatures and with undeveloped or unreliable infrastructure. Developed countries have struggled to avoid serious accidents in primary LiBESS facilities. A second-life application under much more challenging conditions can heighten these risks. Governments must ensure that developing countries do not simply become the e-waste dumping ground for Li-ion batteries. On the contrary, economic and environmental benefits must, whenever possible, be fashioned from an effective circular economy approach that strengthens their critical minerals supplies or takes advantage of other opportunities, such as easing the transition to a zero carbon energy infrastructure. A standard battery management system (BMS) data stream—or, at minimum, a provision that allows access to the manufacturer's BMS data—is critical to ensure that secondary Li-ion batteries are used in a sustainable and safe manner. Such a system is particularly important for developing countries that may not have the means to evaluate the overall integrity of these products.

NOTES

1. This is also an issue for many developed economies.
2. Email exchange with Matthew Keyser of NREL February 2020
3. It should be borne in mind that materials used in batteries are not only the direct product of the mining industry – recycling will need to manage plastics, solvents, electrolytes, and so forth.
4. Email exchange with Chinese Industrial Association of Power Producers, June 2020.
5. For instance, see Unicore's recycling process: https://csm.umicore.com/en/battery-recycling/our-recycling-process
6. Ibíd., pp.8-9
7. Section mostly reflects conclusions reached by Melin (2019, pp. 23-26).
8. This study does not look at Vehicle to Grid (V2G) scenarios as this area does not focus on second-life batteries.
9. See Reid and Julve (2016, pp. 28-30). Also see McKinsey (2019), which estimates second-life batteries providing 200 GwH by 2030.

3 REGIONAL PROFILES

In addition to environmental benefits, the key driver for recycling (if not reuse) of Li-ion batteries is that many components are of significant strategic value. The strategic security interests, in the form of critical minerals and metals reserves, and potential economic benefits apply not only to the repurposing of these key elements but also in providing recycled elements for rebuilt batteries that could make access to the battery recycling and reuse products more cost effective (IESA 2019).

Table 3.1 demonstrates (CRU 2019) that most regions are still developing standards and regulations for battery recycling and reuse practices. The table also (CRU Group 2019) provides a comparative updated summary of regulations in key regions of the world along with some of the major firms participating in recycling of Li-ion batteries. Clearly, China and Europe appear to be the regulatory leaders at present. Also, it is apparent that developing countries are far behind. India is certainly making progress,[1] but there is little evidence of other developing countries following suit.

SOUTH KOREA

South Korea commenced mass Li-ion battery production in 1999 and launched its second-life program for products in 2015 with the expectation that there will be a steady supply of EV batteries ready for transformation to a stationary power provider with backup function.

The EOL management of the batteries is addressed in the Clean Air provisions for emissions with an understanding that the government holds the ultimate responsibility for collecting batteries for recycling or repurposing activities. In 2015, Jeju Techno Park began developing second-life battery reuse valuation technology. The Korea Battery Industry Association (KBIA) developed a standard second-life battery reuse valuation method in 2019. Currently, a standard for a second-life battery grading evaluation method is being developed. KBIA is building EV, energy storage system second-life battery performance and safety evaluation centers in Naju, Jeollanam-do[2], and is preparing to build a recycling center. Companies such as Hyundai Motor, LG Chem, Woojin Industrial Systems, and Incel are also participating in this project.

CHINA

China appears to be recalibrating its recycling efforts in response to initiatives in industrialized nations. It recently announced that as the largest consumer of EVs, it will be developing a series of regulations and public policies "aimed at promoting construction of an end-of-life vehicle battery recycling industry that is environmentally friendly, resource saving and economically beneficial" (CRU Group 2019). There is also a consistent policy to view these devices as containing critical "energy materials" and recycling is a key consideration to maintaining the supply chain of these materials. A significant portion of the worlds' LIBESS systems are in South Korea and China. Both countries are keenly aware of the link between the recycled materials and the battery manufacturers—especially with respect to critical to key materials such as nickel and cobalt, which are not domestically accessible as primary materials.

Batteries from buses and early EVs are beginning to be reprocessed for second life in China. An agreement has been reached between the central government and 16 of the largest battery and vehicle companies, along with operators of telecom towers, to use the batteries as backup power solutions. Demand for this type of energy storage far outpaces the supply of used batteries. To date

TABLE 3.1: **Geographical Overview of Standards and Regulations**

Status	China	Europe	USA	Japan	Korea	Africa	South America	India
Regulations on EV batteries for Recycling	✓	Battery Directive and the amending of 2008/98/ EC allowing for an object to be transferred without having to be declared a waste	—	—	Clean Air Conservation Article 58 Operation of a low-emission vehicle	—	—	—
General Regulation on LIB Batteries	✓	✓	Universal waste (US 40 CFR 273.3) further regulated by Status	Act on the Promotion of effective Utilization of Resources, 2001	—	—	—	—
Regulations on 2nd Life EV batteries	✓	—	—	—	—	—	—	—
Extended Producer Responsibility	✓	✓	✓	—	—	—	—	—
Recycling Efficiency target	Hydrometallurgical 96% targeting Ni, Co and Mn Pyrometallurgical 97% targeting Nickel and Rare Earths	50% of the weight of the end of life battery is recycled	—	—	—	—	—	—
Major Recyclers of LIB	Brunph, GEM, Gangfeng, Fangyuan New Energy Materials, Hyayou Cobalt, Jingsu Miracle Logistics, Taisen	Umicore, Saft, Recupyl, and Accurec	Retriev, RCI, Emerging companies include; Sungeel-Metallico, Battery Resourcers	NRCC, JMC, Sumitomo, Dowa Ecosystem, JX Nippon	SungEEL Hi-tech, Koba, Torecom and TMC	—	—	Tata Chemicals, Raasi Solar and Mahindra Electric

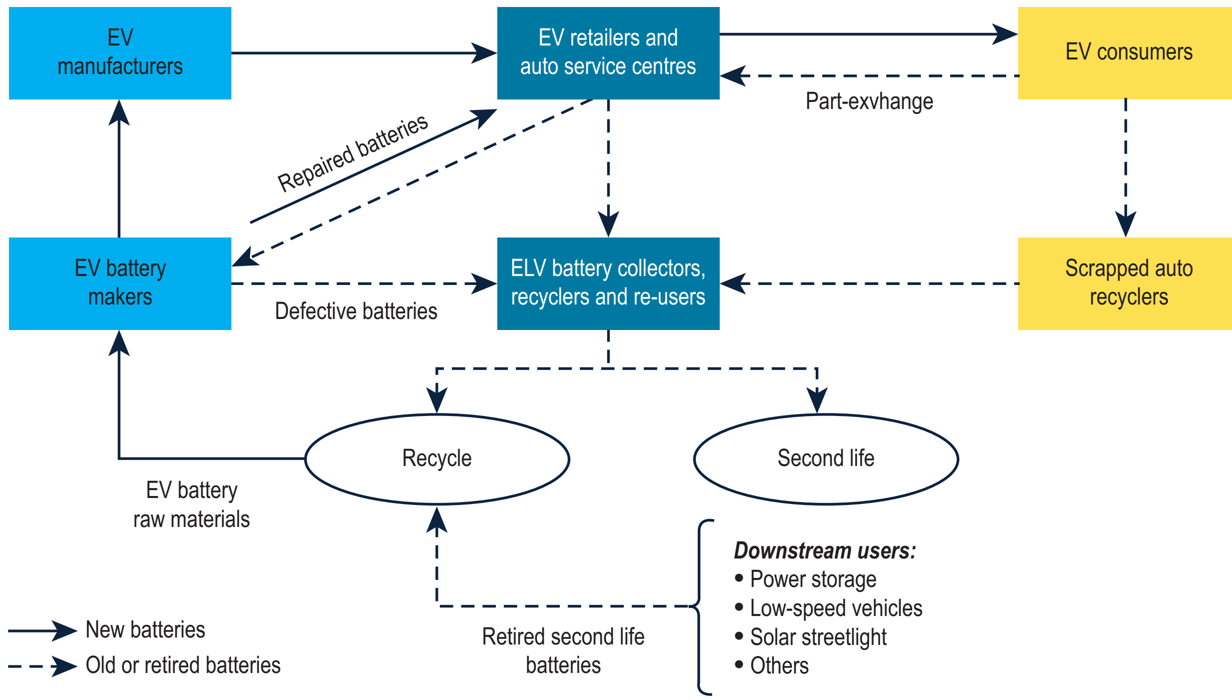
(continued)

TABLE 3.1: ***(Continued)***

Status	China	Europe	USA	Japan	Korea	Africa	South america	India
Major Recycle Associations of LIB	Waste Battery Recycling Commitee China Battery Industry Association	European Battery Recycling Association and ReCharge	NAATBatt	Battery Association of Japan	Korea Battery Industry Association	South Africa's Electric vehicle Industry Association is looking at recycling as part of the broader issue of EV integration	—	—
Summary	Current policies prioritize 2nd life EV batteries and promote marketization improving information transparency, recycling efficiency and R&D for recycling technologies	Policies guide EV producers and battery makers to participate in battery recycling	No regulations specifically for EV batteries	Japanese Auto makers have led the recyling of EV batteries. Li-ion batteries are subject to further regulation under the Electrical Appliance and Material Safety Act.	South Korea Battery Associations has collabrated with the National University to pioneer EV batery recycling		No regulations and widespread problems with properly recycling Pb batteries	To date, India does not have any specific regulations or guidelines around the effective disposal and or recycling of Li-ion batteries
		Recycling industry is relatively mature compared to each other regions. EV producers are acutely aware of the importance of recycling	US DOE launched first LIB recycling research center ReCall at ANL	Japanese joint venture (Sumitomo and Nissan) 4R Energy was awarded the first UL 1974 standard for EV battery reuse			Fuel efficiency standards vary from none to world class in chile, there are no EV specific regulations	

Source: Authors.

FIGURE 3.1: China: Who are Participants in the Recycling Network?



Source: CRU Group 2019

10,000 tons of EOL batteries have been used as backup power solutions corresponding to a capacity of 800 MWh or 2% of need (Melin 2019).

The major actors and processes in China's recycling/reuse network are outlined in Figure 3.1 (CRU Group 2019). Interestingly, it is apparent that reuse is well integrated into China's overall recycling scheme for Li-ion batteries.

UNITED STATES

The crucial value of recycling/reusing Li-ion batteries is being increasingly appreciated in the United States. For example, the US Department of Energy recently launched its ReCell program. US Secretary of Energy Rick Perry explicitly announced the recycling program as a means to close the 'critical metals' gap. He said that "America's dependence on foreign sources of critical materials undermines our energy security and national security. US Department of Energy will leverage the power of competition and the resources of the private sector, universities, and the National Laboratories to develop innovative recycling technologies, which will bolster economic growth, strengthen our energy security, and improve the environment" (Perry 2019).

The US Energy Storage Association recently released a report examining the status and future of EOL Management of Lithium Energy Storage Systems (US Energy Storage Association 2020). Not withstanding its relatively nascent status, most of the relevant activities relate to recycling; second use batteries are limited in their application to pilot demonstrations and a few small projects. EOL options for LiBESS have yet to develop into a consistently regulated and economic activity. Areas of innovation being pursued by a range of universities and labs include:

- recycling designs
- direct cathode recycling
- improved recovery of other materials in LiBESS
- increased use of recycled materials in new batteries

EUROPE

Although the European Union is a mature market with respect to traditional battery recycling, there is only one facility that links cathode manufacturing and recycling: Umicore. This natural partnership deserves greater encouragement, as it can add overall value to the process. Indeed, the relationship between the recycler and the cathode manufacturer partly explains why EV recycling in Asia has been the most robust globally.

Other recycling companies in the European Union are SNAM and Recupyl (France), Redux (Germany). Batrec (Switzerland) and Euro Dieuze (France) are part of the large environmental service company Veolia (but not part of the original cathode manufacturing process). Startups include Duesenfeld (Germany). Meanwhile SungEel Hi Tec (Korean recycler) is proposing a processing plant in Hungary and possibly a neometals plant.

This battery recycling experience will certainly help with the organization and collection of large format EV batteries. Although no specific directive has been taken with regards to the EV batteries (they would be managed as “industrial” under 2006/66/EC) one proposal from the EU Council Presidency in 2017 entailed amending 2008/98/EC so that an object (EV battery) could be transferred from one holder to another without the intent to discard. This would imply that the battery could be taken for reuse rather than being classified by default as waste.

New business models are being implemented by original equipment manufacturers (OEMs) in some European countries whereby companies such as VW and Renault have installed dedicated in-house recycling processes that allow them to retain materials at end of life. Some cell suppliers are now offering lower prices to OEMs who guarantee to return at least 80% of materials sold to them at end of life. Such packs may never reach the developing world.

AFRICA

Africa is one of the regions that would most directly benefit from a robust circular economy program for Li-ion batteries. The continent is, by far, the poorest region with respect to electricity access. There are a small number of initiatives in Eastern Africa exploring the use of second-life batteries for energy storage/backup services. The Faraday Battery Challenge included a project in Kenya that looked to extend the life of vehicle Li-ion batteries through repurposing for a Kenyan solar home system provider, M-KOPA.[3] Supported by the Shell Foundation, Aceleron is working with an organization called BBOXX in Kenya and Rwanda to test the use of second-life Li-ion batteries for energy storage purposes. Their initial conclusion is that used Li-ion batteries are superior in performance to lead batteries. They are looking to develop a service model that will commercialize their localized, circular economy approach.[4]

Along with these two projects, a number of related projects have been selected as candidates for the Global LEAP Awards competition for the Solar E-waste Challenge, in which some projects also examine the repurposing of Li-ion batteries. These include the Solaris Off Grid project in Tanzania, which looks at ways in which spent batteries from solar home systems can be effectively recycled and replaced with second-life batteries; and a Hinckley recycling facility in Nigeria, which is exploring a process to reuse battery cells through the production of new products from off-grid solar batteries. In Kenya, WeTu, a solar-powered lighting provider, is establishing seven battery collection points for fishermen who use solar-powered lanterns. Finally, in Benin and Burkina Faso, a project called Lagazel is working to develop capacity in Sub-Saharan Africa to reuse end-of-life Li-ion battery cells in second-life battery packs.[5]

The South African government has also commissioned a report *Lithium Battery Recycling* that addresses the sustainable management of Li-ion batteries, with a particular focus on recycling. The report identifies two outstanding issues: few regulations around the disposal of Li-ion batteries after their first life and a lack of relevant products in domestic markets, as EVs are only now being introduced in the African vehicle market.

LATIN AMERICA

In Latin America, battery recycling is typically covered under broader solid waste management regimes. This is a less than reassuring picture. Currently, only 55% of solid waste is properly managed in sanitary landfills, implying significant failures in collections and proper disposal.

Several countries have regulations that cover lead battery recycling: Brazil, Chile, Colombia, Costa Rica Mexico, Paraguay, and Peru. However, there are no analogous regulatory regimes for Li-ion batteries, meaning there is almost no infrastructure for recycling e-waste or batteries. Instead, these are typically exported to Europe or the US for recycling.

By 2020, 80% of Latin American countries plan to implement e-waste and battery collection programs, such as an Extended Producer Responsibility model. These plans are considered fairly ambitious in view of the existing infrastructural challenges yet to be overcome.[6]

REPORTING AND MEASUREMENT STANDARDS AND LIABILITY[7]

In most regions, robust reporting/measuring and liability regimes are still lacking. Meanwhile, industry standards continue to be developed to address these gaps. Originally focused on safety issues, standards now also address a wide range of performance issues. With regards to EV batteries, there is a recognition that second-life standards will have a role to play, with the most notable platform being the UL 1974 standard, although it mainly focuses on lead acid batteries.[8]

However, a serious gap—in both developed and developing countries—relates to the lack of harmonized standards for Li-ion batteries. The codification of lithium manufacturing and performance standards has been difficult for a variety of reasons. Most significantly, there is a wide range of sectors responsible for developing the relevant technologies, such as phone, appliance, vehicle, and power providers. Uniform reporting and measurement tools must be developed for these technologies. Appropriate standards need to tackle: energy density (Wh/kg); power (W); energy efficiency; life cycle patterns; and safety parameters (including the development of vibration, mechanical shock, electricity, and temperature tests) (Aristyawati et al. 2016).

The same lack of coordination and harmonization exists with respect to the issue of liability and the respective roles and responsibilities of the initial manufacturer and the eventual users as it makes its way from the EV to a stationary source. Areas of potential liability include accident and injury; product recall and reputational risk; data loss; and the environment. These products are potentially dangerous chemical goods, with attendant risks of combustion and explosion. Liability issues are also relevant throughout the life cycle of the product—from the planning and design to the manufacturing to the operation stages of the product (as governed by relevant operational guidelines). A full life value approach will ensure that ownership and risks (and, by extension, liabilities) are defined throughout the operational life of the battery. Maintenance and regeneration protocols for the battery's life in energy storage systems should be considered when developing warranties for LiBESS. The respective maintenance and regeneration processes developed for batteries will play a critical role in determining the length and quality of its service life.

NOTES

1. See https://economictimes.indiatimes.com/industry/auto/auto-news/lithium-ion-battery-recycling-presents-a-1000-million-opportunity-in-india/articleshow/71341593.cms?from=mdr
2. The Jeollanam-Do province has a master plan to develop an EV/energy storage system battery reuse, refabrication, and recycling industry research & development and demonstration center. Tentatively scheduled for 2021, the 8,600m2 used battery center will be comprised of 5 buildings including a warehouse, testing facility, safety testing facility, and environment testing facility. (Information provided by KBIA).
3. See activities under Advanced Battery Life Extension (ABLE).
4. See https://shellfoundation.org/learning/aceloron-pilot-lessons-learnt and https://shellfoundation.org/apps/uploads/2019/06/Aceleron-Field-Trial-02019-06
5. See Global Leap Awards Solar E-Challenge Round 2.
6. Hugo Alvarenga, ORBIS Compliance. Article in April 2018 issue of Incompliance Magazine.
7. See Techc@re.
8. It should be noted that the International Electrotechnical Commission (IEC) is proposing a new work item. See "Requirements for reuse of secondary batteries" at https://www.iec.ch/dyn/www/f?p=103:20:0::::FSP_ORG_ID,FSP_LANG_ID:1290,25

4 FUTURE AREAS OF RESEARCH AND RECOMMENDATIONS

Developing countries must engage on this issue as a matter of some urgency: the collection and retention of valuable materials from Li-ion batteries could represent a strategic economic resource. It could also help ease the cost of countries embarking on a clean energy transition. Although some commodities, such as lithium, are at present less economic to recycle than to extract as a primary resource, that situation is unlikely to continue indefinitely.

If responsibly designed and managed, recycling and/or reuse activities could represent a sustainable and growing revenue streams providing steady 'blue-collar' income. It should also provide significant environmental benefits, from mitigation of the environmental impact of local landfills (discarded batteries) to easing the market pressures driving primary extraction practices. The more key elements and technologies are made available through recycling/reuse, the less reliance on mining to provide these resources (ISEA 2019).

As the demand for these batteries and their materials grows, it should be increasingly advantageous to extract critical resources using these technologies. As already witnessed in Japan and Korea, the phenomenon of 'urban mining' is bound to increase over the coming years. Will countries be satisfied to simply export their 'used' EV batteries for other countries to exploit (and re-sell the resources) or are there sufficient incentives to become part of the global battery marketplace and develop the recycling/reuse industry locally?

COLLECTION AND TRANSPORTATION OF LITHIUM-ION BATTERIES

In developing countries, collection of Li-ion batteries for the purpose of recycling/reuse is very much in its infancy (Manhart et al. 2018). In fact, overall there is a dearth of research in this area, when compared to the literature surrounding recycling and reuse techniques. In other words, most research takes the sufficient supply of Li-ion batteries for recycling and reuse as a given, whereas in most areas of the world, with the exception of China and South Korea, this is a critical issue. Areas where additional research could prove useful include:

- **Minimum requirements:** What is the threshold of 'first life' users in making their batteries available for collection? Which collectors are favored over others and why? Which technical solutions best resolve issues around safety and environmental impact relating to collection and transportation of these goods?
- **Regulations:** What changes/additions should be made regarding regulations on the international trade of expended batteries and do those regulations serve as barriers or incentives for recycling/reuse?
- **Classification:** What are the most effective modalities in developing countries for the disassembly, sorting, and classification of Li-ion batteries?
- **Owner and business models for reuse**: What are the most effective business models which will expedite the easy transfer of spent EV batteries to LiBESS users?[1] What are the prospects of developing countries adopting such practices? What lessons have we learned from other regions in seeking to enhance the economic attractiveness of a circular economy approach to LiBESS? What is the status quo in terms of battery recycling, in general, including lead batteries, and how might this best be augmented by Li-ion batteries?

- **Regional priorities in developing countries**: What might be the best approach on recycling and repurposing for developing countries? Decentralized recycling/reuse stations or more centrally located facilities? To what extent should regulations and standards be developed on national or regional bases?
- **Standardization:** While a single predominant type of Li-ion battery is unlikely to emerge, measurement and reporting protocols for LiBESS products (covering energy density, power, energy efficiency, and a range of safety measures) can be harmonized and coordinated, as well as codifying appropriate measurement, reporting, and labelling practices.
- **Liability:** Common liability practices should be formally developed and agreed upon, covering the full life cycle of Li-ion products, including collection and transportation practices.

Future research is needed for other issues common to reuse and recycling, such as:

- **Co-ordination:** What sort of coordinated approach should be taken to the principle of extended producer responsibility for second-life LiBESS?
- **Extended producer responsibility:** What are the basic infrastructure and legal requirements necessary to make EPR functional?
- **Relevance of lead acid batteries:** What is the status quo in terms of battery recycling, in general, including lead batteries, and how might this best be augmented by Li-ion batteries?
- **Challenges:** Are there common or specific logistical challenges related to developing countries?

REUSE

The reuse of Li-ion batteries (and other components), particularly from vehicular Li-ion batteries to stationary energy storage batteries, is still at an early stage, as is research on the subject, despite its significant potential contribution to local economies. Areas ripe for further research include:

- **Potential for repackaged LiBESS in supplying/supporting large scale energy storage systems:** Most of the research has focused on small grid power, often for individual homes or buildings. Despite current challenges (significant safety and reliability risks), what might the prospects be for reused systems that are financially competitive at a larger scale? There are four possibilities:
  - Distributed energy storage (residential and small business)
  - Utility scale energy programs (Li-ion batteries have been gaining market share in this segment)
  - EV charging (e-mobility will eventually expand in Africa)
  - Modular based (lead battery replacement)
- **Piloting:** Reuse pilot case studies for community based and micro grids in a range of developing country ecosystems, with varied geology and climate (Ambrose et al. 2014).
- **Capacity:** How ready are host countries to adopt reused batteries as part of their grid or buildings/home power systems?
- **Research:** Research is needed on the suitability of automotive battery packs and their chemistry for various ambient environments. A battery pack designed to work at up to 35°C ambient temperature may not be suitable for reuse in another country where equipment temperatures (including the effect of solar loading) can swiftly exceed 80 °C.
- **Social impacts:** Develop a robust inventory of environmental and social impacts of full life cycle of used batteries, covering production, use, and decommissioning.
- **Benchmarking:** Develop locally robust benchmark figures representative of current good international industry practices.
- **Testing and grading of first use batteries for reuse**: Perhaps consider developing an ISO type system of standards for reused batteries.
- **Manufacturing improvements:** How best to improve battery pack assembly for reuse to mitigate safety and environmental impact concerns?
- **Second-life options:** Demonstrate utility of reused systems for the full range of stationary power uses. As many as 14 different uses of LiBESS have been identified. Are all of these suitable for reused batteries; are some more viable than others?
- **Outreach:** What elements should be included in developing local awareness raising programs on the utility of second-life Li-ion batteries for developing countries (Sovacool 2018)?

- **Grid systems:** Are energy storage reuse practices for LiBESS compatible with the grid systems in developing countries—in particular given the need for a complex control system and trading of balancing/transmission services?
- **Testing:** Can second-life batteries be accurately and effectively tested for reuse? This is vital from time and cost perspectives. How might existing technologies be efficiently harnessed to yield basic information about the battery and hence determine optimal applications?
- **Flexibility:** What research will best answer outstanding questions about the degree of flexibility with which different Li-ion batteries can be used in second-life applications within a single system?
- **Direct recycling practices:** more environmentally benign direct recycling practices could be easier to adopt in developing countries
- **Holistic approaches in enhancing recycling:** the degree to which batteries can be designed to account for easier disassembly and collection practices
- **Sorting, classification, and labeling practices:** integrating these steps with collection should open up the market considerably

RECYCLING

While the state of research in this area is appreciably more advanced than is the case with either collection or reuse, its utility, particularly in the context of developing countries, is another matter.

Given the relative level of sophistication required to recycle six distinct types of Li-ion batteries, there is a need to develop local capacity in developing countries. What kind of training systems might work best in those situations? Other areas to examine include:

- **Direct recycling practices:** more environmentally benign direct recycling practices could be easier to adopt in developing countries
- **Holistic approaches in enhancing recycling:** the degree to which batteries can be designed to account for easier disassembly and collection practices
- **Sorting, classification, and labeling practices:** integrating these steps with collection should open up the market considerably

RECOMMENDATIONS

Overall, the goal of future renewable energy storage globally is to build an innovative, green, market-oriented system, by implementing the following concepts: long-term design; low carbon manufacturing, safe operation and maintenance; and green recycling. In the context of developing countries, the following steps might be considered in adopting a robust recycling/reuse regime by policy makers.

In the nearer term:

- Initial awareness raising among relevant decision and policy makers to factor in environmental and social impacts, including those related to recycling/reuse EOL options when deciding upon battery systems for providing low carbon transportation and/or power needs.
- Raise awareness on access to these centres for owners and penalties for non-compliance or incentives for compliance. Dedicated consumer education drives and product stewardship programs would be useful tools in this regard.
- Identify what makes the most sense for the relevant country (then implement):
    - Is the country naturally endowed with materials required for batteries?
        - If so, what is the capacity and economic feasibility to make best use of these resources?
        - Is there a responsible, climate smart, inclusive and transparent mining regime in place?
    - Is that country importing or building battery capacity for its transportation and/or power systems (on and/or off grid)?
        - If so, what is envisioned for the EOL of these batteries and can materials or repurposed technology be kept within the country?
- Develop a framework for training and upskilling in triaging, battery manufacturing, occupational health and safety standards; servicing of batteries, dismantling, and recycling and reusing.

- Collection should be specifically addressed in the recycling/reuse plans, including incentives and models for effective collection techniques.
- Develop a specific recycling/reuse regulatory regime—given the very different challenges from lead batteries disassembly and recycling, countries/regions should develop explicit regulatory frameworks for the full range of Li-ion batteries in domestic/regional operation
- At a minimum, metrics for helping governments evaluate these regimes' effectiveness and inform appropriate public policies would include:
  - resource efficiency of the process;
  - water use and quality;
  - GHG emissions;
  - occupational health and safety;
  - community contributions; and,
  - others
- Formalize the battery collection regime—too often, even with lead batteries, the collection and transportation of these potentially hazardous products is not formally regulated.
- Ensure that local research capacity in battery technology is built and maintained. Develop an active network involving industry, governments, academia and civil society to create a sense of 'common ownership' on the issue.

Some longer term recommendations, requiring coordinated action beyond the country level would include:

- Develop efficient distribution/transportation centers. The type of electricity service being provided also plays a critical role in the relative complexity of collecting and transporting EOL batteries—does the power system envisioned include planned replacement dates and service agreements?
- Work actively and seek advice from countries with previous experience in this burgeoning area (China, South Korea, Japan) and where active research is underway (NREL, Europe, etc.) and from successful firms.
- Areas of particular interest to developing countries include: (i) systems for integration and management of reuse and recycling practices; (ii) extending producer responsibility; (iii) strengthening regulatory and public policy frameworks; (iv) enhancing economic attractiveness of recycling and reuse of Li-ion batteries; and (v) health and safety considerations.
- Develop and implement relevant public policy measures—for example, in setting a universal minimum recycling target to be imposed on recyclers in each country. Only recyclers that can achieve this target should be permitted to recycle the packs. (Countries may choose to exceed the target level.)
- Press for co-ordinated/harmonized standards for recycling/re purposing of Li-ion batteries in reporting protocols covering the following elements: energy density; power; energy efficiency; temperature resilience; and life cycle.
- Develop clear liability guidelines that are globally recognized. Stages would cover the full lifetime of recycled/re-purposed products including inception/design; manufacturing; usage; and, disposal activities.
- Develop a robust trade and investment regime that will expand opportunities for developing countries to become active participants in the LiBESS global regime.

In future, two recycling approaches will be required. One is for the recycling of existing batteries, that is, Li-ion batteries that have been or are about to be spent. These will inevitably still feature relatively cumbersome and inefficient reuse and recycling practices. The other approach is for the next iteration of Li-ion batteries. This next generation of Li-ion batteries must be designed with a view to easing EOL challenges. Governments will need to develop discrete regulations and regimes for each of these systems. Later models of Li-ion battery should be tested for their internal consistency, and their recycling capacity, with a transportation infrastructure in place that focuses on developing a distinct Li-ion collection network.

NOTES

1. http://theconversation.com/africas-growing-lead-battery-industry-is-causing-extensive-contamination-130899

GLOSSARY

2030 Agenda for Sustainable Development: the UN based sustainability road map for the globe, comprising 17 Sustainable Development Goals (SDGs).

Circular Economy: an approach to economic development that takes into account the full material impacts of products throughout their duration. Focuses on four elements--reduced use, re-purposing, recycling, and disposal--to ensure net zero environmental impacts.

Electric Vehicles (EV): motorized vehicles powered by electricity

Climate Smart Mining Initiative (CSMI): an initiative managed by the World Bank Group's Energy and Extractives Global Practice, the CSMI is a partnership of governments, lending agencies and industry working towards implementing principles and practices that manage GHG emissions and limit the environmental impacts on local communities and ecosystems. Members include the WBG, (IDA and IFC), the Dutch government, Anglo American and Rio Tinto.

Energy Storage Partnership (ESP): a partnership launched by the WBG in May 2019, to complement the World Bank's US$1 billion battery storage investment program announced in September 2018. As a test bed for capacity building and the dissemination of knowedge on power systems it focuses on:

- Development of testing protocols and validation of performance;
- Flexible sector coupling;
- Decentralized energy storage solutions;
- Procurement frameworks and enabling policies for energy storage; and
- Recycling systems and standards.

Global Battery Alliance (GBA): initiative out of the World Economic Forum that promotes a circular economy approach to the design, deployment, second-life and eventual disposal of LiBESS.

Global Leap Awards: initiative intended to promote innovation in developing countries, particularly as it relates to energy efficiency technologies and practices. One of its current projects is focusing on promoting solar e-waste recycling (including batteries).

Lead Batteries: the most successful recycled product globally (due to its toxicity and relatively consistent treatment to end of life). Not an effective product as a stationary power source/backup, particularly when compared to LiBESS technologies.

Lithium-ion Battery Energy Storage Systems (LiBESS): the main subject of this report, which explores the recycling and reuse capacity of Li-ion batteries once they have expended their first life capacity, virtually all in the transportation sector.

Batteries are typically defined according to the chemicals used at cathode and anode:

Examples of Positive LiBESS Electrode	Examples of Negative LiBESS Electrodes
• Lithium nickel manganese (NMC) • Lithium nickel cobalt (NCA) • Lithium manganese (NMO) • Lithium Iron Phosphate (LFP) • Lithium Cobalt (LCO)	• Graphite • Lithium Titanate (LTO) • Hard Carbon • Tin/Cobalt Alloy

Paris Climate Agreement: UN based climate change agreement whereby nations agreed to develop national plans to address climate change through Nationally Determined Contributions (NDCs) and a long-term goal of avoiding a global temperature increase of more than 2°C.

UL 1974 Regulations: standard covers the sorting and grading processes for battery packs and modules.

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