Circular batteries

Circular business models for the lithium-ion battery industry

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Contents

If the world is to develop sustainably, run efficiently and find new sources of value, we need to reduce the waste produced from all sectors, including batteries.

Responsible consumption and production

Achieving this contributes to the United Nations' Sustainable Development Goal 12, which focuses on 'doing more and better with less' in order to provide better social and environmental outcomes globally.

The lithium-ion battery industry has implications beyond Goal 12. When combined with circular economy principles, the industry could generate significant economic, environmental and social value. The industry also influences Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation and Infrastructure) and Goal 17 (Partnerships for the Goals).

Foreword

The global challenge to develop a decarbonized and circular economy requires a huge transformation of global business models.

Clean energy transition brings opportunities for investment and job creation and represents one of the most effective responses to this global challenge. It can create a range of environmental sustainability, efficiency, digitalization and technological innovations. To unlock these opportunities, the nexus of renewable energy, smart grids and demand electrification will play an increasingly central role.

The only historical challenge for the continued growth of renewable energy has been the possibility to store electricity. In the past it was achieved mainly through electricity conversion to other forms, such as gravitational energy in pumped hydro storage plants, with limited application potential. Batteries are a game changer – thanks to the extraordinary evolution they have undergone – becoming an effective solution to extensively apply energy storage in power plants, grids, electric vehicles, and residential distributed energy resources.

A clean energy transition underpinned by battery technology must be sustainable and not create further externalities in terms of resource consumption or waste creation. It has to take place in a circular economy context right from its initial stages.

In recent years, we have witnessed a strong technological acceleration in the battery sector, in terms of performance and costs leading to uptake in a diversity of applications. This growth in uptake of battery technologies increases the need to design circular economy design chains, not only in regards to resources but also the business models and the institutional and regulatory context.

This study by Arup represents an important contribution in this direction. Taking a quantitative *and* agile approach, the research addresses the issue in a strategic manner through the entire supply chain – as it should within a circular economy framework. This allows us to understand the key issues and opportunities in terms of design, raw materials, models of use, and closing whole-of-life cycles. Furthermore, the methodological approach to address new topics with an integrated decarbonisation and circular economy focus is best-practice and will be fundamental to successfully achieve the transition to a new economic model.

Luca Meini
Global Head of Circular Economy – Enel Group

Executive summary

Lithium-ion batteries (LIBs) will play an important role in the required shift to a more renewable, resourceful and low-carbon future. However, the ways in which LIBs are currently made, used and disposed of are incompatible with this sustainable future.

The current linear lifecycle of most batteries leads to adverse environmental, social and economic outcomes globally.

The circular economy presents an opportunity to address these adverse outcomes and shift to more sustainable and resilient supply chains.

It is expected that business models based on circular economy principles, known as Circular Business Models (CBMs) represent a US$4.5 trillion global growth opportunity that can contribute to sustainable economic development.

This report, *Circular Batteries,* aims to harness circular economy thinking and stimulate leadership in the LIB industry by:

- Analysing the current state of the industry
- Outlining how CBMs could, or already do, apply to the LIB lifecycle
- Recommending ways forward for industry stakeholders.

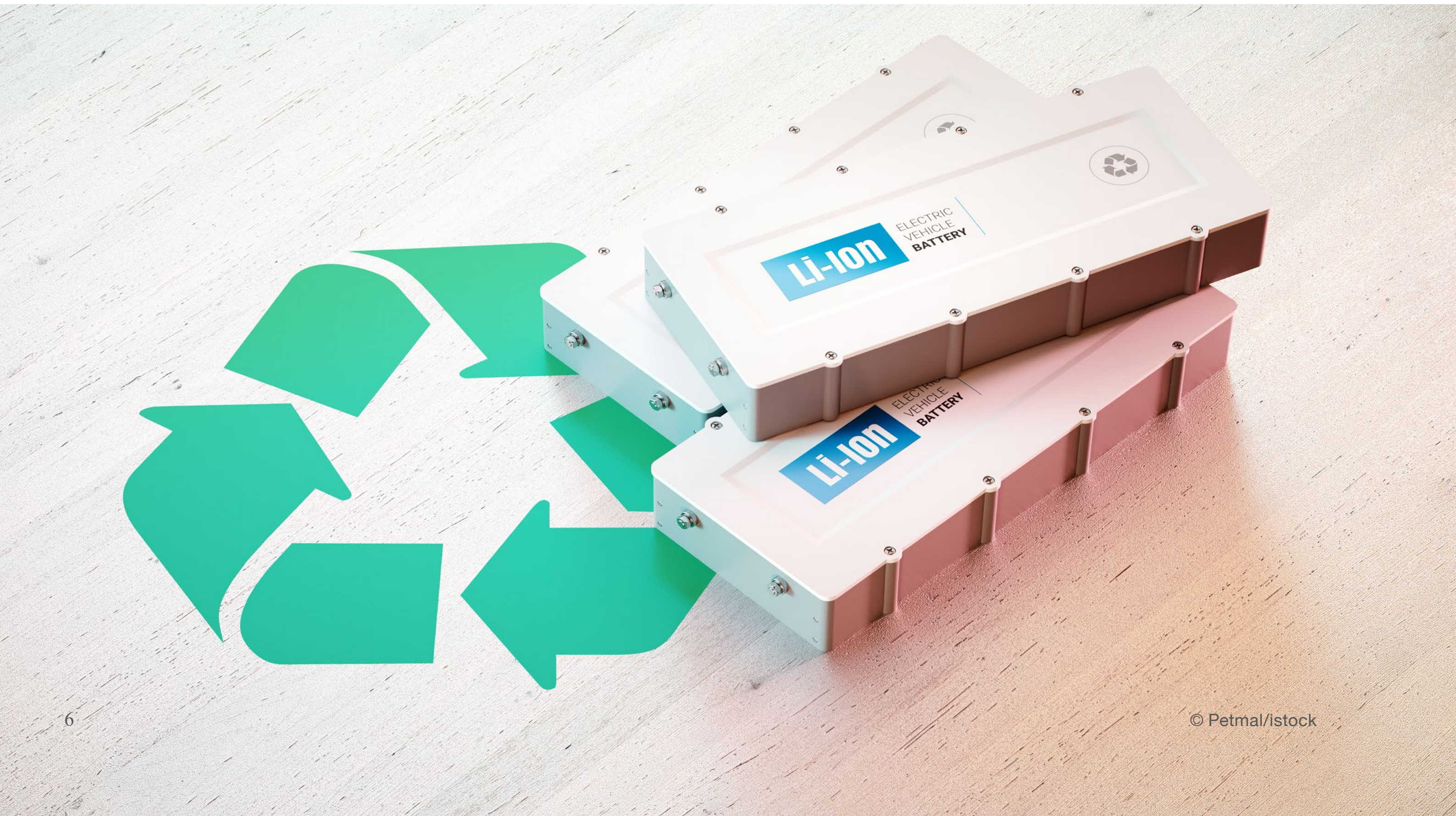
US$4.5tn

CBM global growth opportunity

Through research, interviews and application of circular economy ideas, this report describes the significant opportunities for value creation and new enterprises that are both present and ready to be explored by industry participants globally.

With exponential growth anticipated in the uptake of LIBs globally, policymakers, industry and investors need to work together to establish effective policy, technology and business models that facilitate a circular economy for the industry.

To unlock these opportunities, the following key recommendations are made for industry stakeholders.



Key recommendations

Policymakers should foster a supportive regulatory, research and business environment for CBMs locally and internationally.

- Implement product stewardship schemes to allocate responsibility for LIB components and materials
- Develop financial incentives and use policy levers to spur demand for circular solutions
- Work with industry and across governments to facilitate standardisation where appropriate

Industry should demonstrate leadership and collaboration through partnerships, data sharing initiatives and designing for reuse and disassembly.

- Address gaps in data and information for both new and existing businesses
- Design batteries for cascading reuse and ease of disassembly
- Lead partnerships to develop scalable projects that address local and global environmental concerns

Investors with social and environmental impact objectives should work with government and industry to coordinate and prioritise investment into the most effective CBMs.

- Leverage impact investment to achieve beneficial social and environmental impact alongside financial return
- Consider the resilience impact and benefits of CBM opportunities
- Coordination and prioritisation of investment into the most effective CBM opportunities
- Work with industry and policymakers to develop conditions that promote CBM investment

Together, the LIB industry will need to increase collaboration and coordination in order to loop material flows and increase the value kept in the supply chain.

- Establish, grow and fast-track partnerships across and outside of the supply chain, and grow global initiatives
- Decarbonise production processes and national grids
- Standardise battery design and data management processes, including labelling and materials passports

Product and process design

The World Economic Forum (WEF) estimates, that production emissions from LIBs in 2030 could easily be halved to around 100 Mt at negative cost, and therefore reduce battery costs by 23% while also reducing associated emissions.

Circular supplies

By 2025, it is estimated the processing of materials and electro-chemical production stages of the value chain will be worth US$41bn and US$297bn, respectively.

Sharing platforms

Globally, if 50% of electric vehicles (EVs) became vehicle-to-grid compatible, 17 Mt of carbon emissions would be saved per annum and US$22bn of additional value would be created. Vehicle-to-grid solutions could lower costs for electric vehicle charging infrastructure by up to 90%.

Product-as-a-service

The mobility-as-a-service market is anticipated to be worth US$70.4bn by 2030.

Lifetime extension

The WEF estimates that if 61% of EV batteries were re-used, 20 GWh of energy storage systems (ESS) would be avoided, saving 1 Mt of CO_2 and US$2bn in 2030, increasing in the long-term.

Refurbish and maintain

The effect of increasing repair of faulty batteries from 80% to 95% by 2030 is estimated to retain 30 GWh of battery capacity. This equates to 2 Mt of carbon emissions and US$2bn saved in 2030. A recent study showed that up to a 31% increase in profit can be achieved if remanufacturing is integrated in LIB supply chain networks.

Recycling facility

In 2030, based on current policies, the number of spent batteries will represent around 6.5% of the 2030 demand. In Australia alone, the value of recoverable metals from the 138,000t of LIB waste anticipated in 2036 is estimated to be between A$813m and A$3.09bn.

Introduction

The market for batteries is expected to grow significantly as a result of the increased uptake of electric vehicles as well as residential and utility-scale energy storage systems.

LIBs are high-density rechargeable batteries currently used in businesses, homes and, in ever increasing numbers, other applications. There are around 4,000 MW of batteries globally, while the International Energy Agency (IEA) predicts there will be more than 100,000 MW by 2030 and over 200,000 MW by 2040.

These batteries will play an important role in the required shift to a more renewable, sustainable and low-carbon future.

However, the ways in which LIBs are currently made, used and disposed of are incompatible with a sustainable future.

Lithium-ion batteries are a key enabler for global decarbonisation.

They can facilitate greater use of renewable electricity across several key industries by offering high energy density storage and a more compact way to store electricity in vehicles and electricity networks.

In electric vehicles (EVs) they will enable different forms of transport with lower carbon intensity than an average internal combustion engine vehicle.[1] LIBs have gained popularity among automobile manufacturers as an alternative to nickel metal batteries used in EVs due to their small size and high energy density.

At the utility scale, they provide flexibility, support and resilience to intermittent renewable energy in the electricity networks. They can also support distributed renewable energy solutions and increase the ability to provide electricity in hard-to-reach communities.

The market for LIBs is growing rapidly.

Driven by technology and cost improvements, we are approaching a tipping point where we expect to see rapid deployment of high-density LIB storage solutions in businesses, homes and vehicles.

Since 2010, the annual deployed capacity of LIBs has increased by 500% globally.[2]

Traditionally used in consumer electronics during the 1990s and early 2000s, LIB applications are moving far beyond this small scale. In particular, they are increasingly being used in mobility applications: EV sales represented 2.6% of global car sales in 2019, bringing the total to 7.2 million – a significant increase from the 17,000 on the road in 2010.[3]

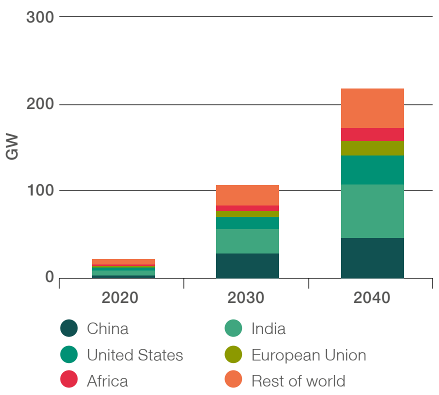


Figure 1: Installed capacity[4]

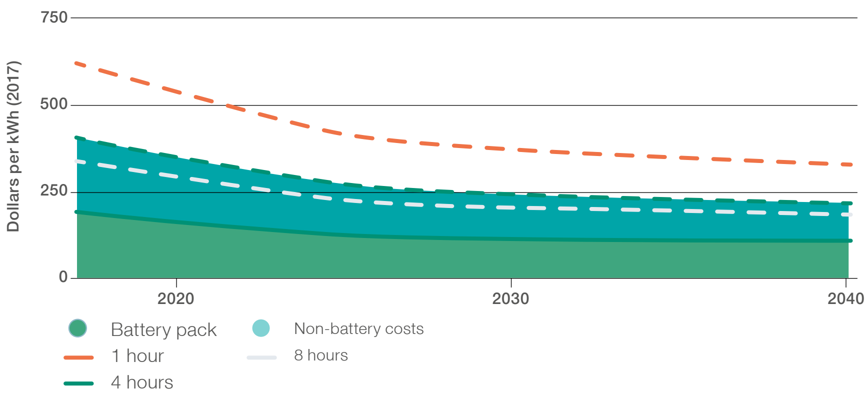


Figure 2: Projected capital cost, based on discharge time[4]

1 Assuming current global average carbon intensity of power generation

2 Global Battery Alliance, n.d., *The Lithium-ion Battery End-of-life Market – A baseline study*

3 International Energy Agency, 2019, *Global EV Outlook 2020*

4 Cairn ERA via Jaffe, 2017, *Vulnerable Links in the Lithium-Ion Battery Supply Chain*

Investors identified **twice as many barriers** as opportunities to the transition to a circular built environment.

The linear supply chain and its rapid growth is leading to unsustainable economic, environmental and social outcomes.

As with most products in the modern world, LIBs follow the linear take-make-dispose supply chain model. This model has many fundamental problems including: supply chain security and flexibility, embodied carbon and energy, water consumption and contamination, labour conditions and, of course, waste.

LIBs contain lithium, other metals and rare earth materials that are mostly mined from the earth in an energy-intensive manner and cause other significant environmental externalities. When LIBs end up in landfill, there are both environmental impacts and significant losses of material value. They also create a potential ignition source, commonly leading to difficult-to-manage fires, causing increasing concern across the landfill management industry.

The circular economy concept provides principles, tools and business models for redirecting this lost value and creating better economic, environmental and social outcomes.

The circular economy is an opportunity for existing players in the LIB industry to create more value, and for new services, jobs and programs to become additional sources of value. This also brings co-benefits to local communities and related sectors.

According to the Ellen MacArthur Foundation (EMF), the main principles of the circular economy are:

- Keeping products and materials in use at their highest possible value
- Regenerating natural systems
- Designing out waste and pollution.[5]

Designing business models around these principles leads to the creation of CBMs which accelerate the transition towards a circular economy. CBMs can be used to reshape existing businesses or inspire new ones.

However, implementing circular models requires a shift in mindset by industry and investors.

The investors interviewed for Arup's *First Steps Towards a Circular Built Environment*[6] report, identified twice as many barriers as opportunities to the transition to a circular built environment.

Greater awareness, research and action in applying CBMs can help industry understand the pathways to unlock the opportunities and solutions to overcome these barriers.

Therefore, more leadership is required to demonstrate and communicate the benefits of the circular economy and how CBMs work. Arup's report, *Circular Photovoltaics*[7] aimed to stimulate and encourage such leadership in the context of the Australian solar PV industry. *Circular Batteries* aims to do the same for the global LIB industry by:

- Analysing the current state of the industry
- Outlining how CBMs could, or already do, apply to the lifecycle of a LIB
- Recommending ways forward for industry stakeholders.

Through research, interviews and application of circular ideas, this report demonstrates the significant opportunities for value capture that are ready to be explored by industry participants.

5 Ellen Macarthur Foundation, 2017, What is the circular economy

6 Arup, 2018, First steps towards a circular built environment

7 Arup, 2019, Circular business models for australia solar photovoltaics

Lithium-ion batteries are a key enabler for global decarbonisation.

LIB technology

LIBs are a type of secondary battery, meaning they can be recharged.

Within the battery cell/s, lithium ions move from a negative electrode to a positive electrode during use, and then back when charging. LIBs use an intercalated lithium compound as one of the electrode materials, rather than traditional metallic lithium used in non-rechargeable (primary) batteries.

They are an attractive energy storage solution because of their high energy density. However, the chemistry, performance, cost and safety characteristics vary across LIB types.

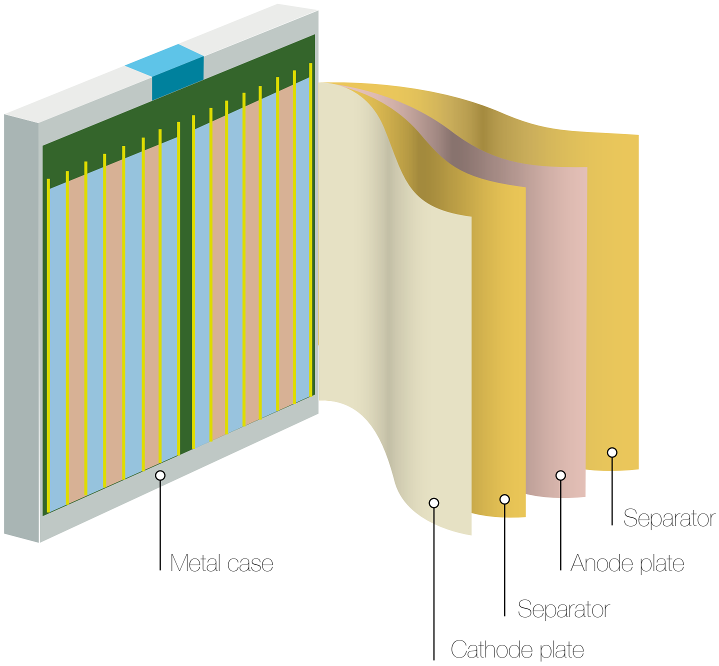


Figure 3: Prismatic Li-ion cell

Common chemistries, their characteristics and uses

	Type	Relative characteristics	Example use cases
LCO	**Lithium-Cobalt Oxide Battery**	Higher energy density Greater safety risks, especially when damaged Limited power Shorter lifespan	Portable electronic devices
LiFePO	**Lithium-Iron Phosphate Battery**	Lower energy density Longer life Reduced safety risk	Energy storage
NMC	**Lithium Nickel Manganese Cobalt Oxide Battery**	Lower energy density Longer life Higher capacity Reduced safety risk	EVs Electric bikes Medical devices
LMO	**Lithium-Manganese Oxide Battery**	Good thermal stability/reduced safety risk Higher power Shorter life Lower capacity	Power tools Medical devices Electric bikes
NCA	**Lithium Nickel Cobalt Aluminum Oxide**	Lower energy density Longer life Reduced safety risk Less thermally stable	EVs Medical devices
LTO	**Lithium-Titanate Battery**	Fast recharge time Lower energy density Longer life Reduced safety risk	EVs Energy storage

NMC batteries are anticipated to be the most popular battery chemistry, followed by LiFePO.

The forecast share of these chemistries to 2026 is shown in Figure 4.[8]

Considering the global demand for LIBs from EVs, alongside the scarcity and cost of cobalt, NMCs with chemistries with relatively higher nickel content and relatively lower cobalt content are anticipated to be the most popular.

While forecasts can be useful for future planning and investment decisions, especially regarding end-of-life (EOL) preparation, there is a high degree of uncertainty around which LIB chemistries will be dominant moving forward. This uncertainty is largely due to the intense levels of competition and research and development (R&D) occurring.

Chemistries are being adapted and new technologies introduced regularly in academia and industry. This poses a challenge to the development of any business models around LIBs, circular or otherwise.

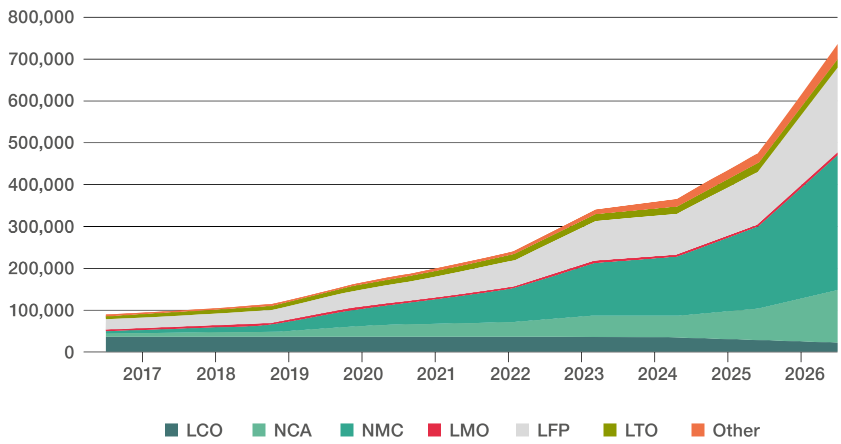


Figure 4: Global Battery Industry Growth Forecasts by Electrode Chemistry, in MWh, 2017-2026.[8]

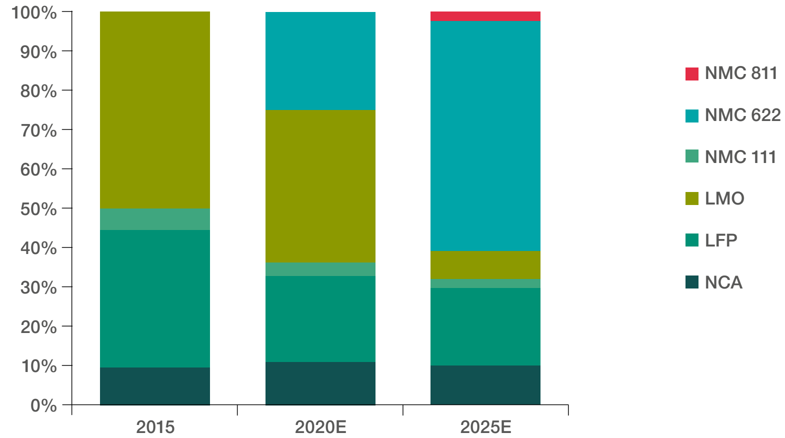


Figure 5: EV Battery Chemistry Market Share – BMO Capital Markets.[9]

8 Cairn ERA via Jaffe, 2017, *Vulnerable Links in the Lithium-Ion Battery Supply Chain*

9 BMO Capital Markets, 2018, *The Lithium-Ion Battery and the EV Market.*
Note on naming convention: NMC 622 indicates a ratio of 6 to 2 to 2 for nickel, manganese and cobalt.

LIB market

Compared to 2018, global battery demand is expected to increase 14-fold by 2030.[10] LIBs are expected to fill much of this demand.

Historically, LIBs have been used almost exclusively in consumer electronics. Now, EVs, especially personal vehicles, are emerging as the largest application category. Electric buses are becoming more common, and prototypes of electric ferries and even planes are emerging.[13]

In 2030, the IEA expects global EV sales to reach between 23 million and 43 million.

The ultimate numbers depend on policies enacted by governments between now and then.[14] It is clear, however, that the scale will be far beyond current demand.

Use at the utility scale is also anticipated to grow, with energy storage systems, data centres and telecoms utilising large batteries. At the time of writing, the largest operational utility battery is the 250 MW Gateway project by LS Power in San Diego.

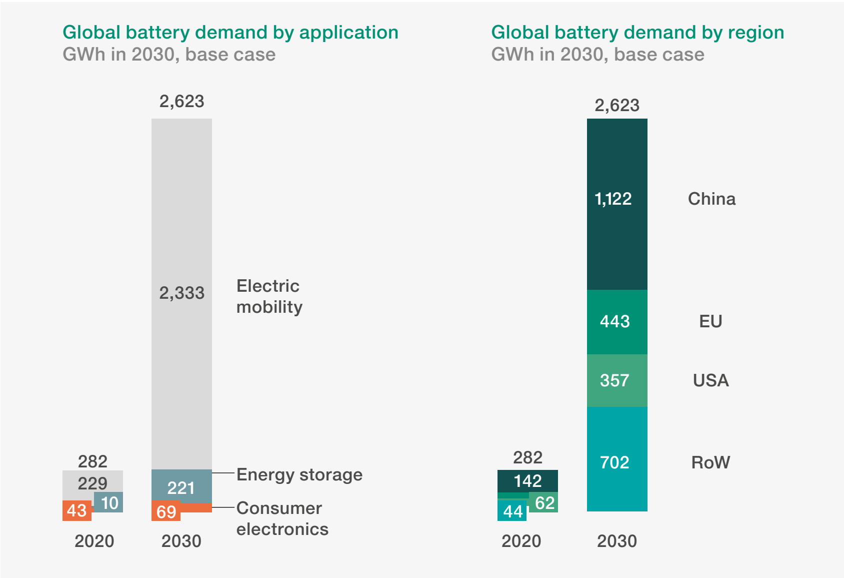


Figure 6: Global battery demand by application and region.[12]

This expanded battery will provide dispatchable power to support renewables in the region, ancillary services and virtual inertia to the grid.[15]

The global LIB market size is estimated to hit nearly

US$92.2bn

by 2024,[11] as a result of the increasing demand from EVs.

10 World Economic Forum, Global Battery Alliance; McKinsey analysis

11 Markets and Markets, 2019, *Lithium Ion Battery Market by Type*

12 World Economic Forum, Global Battery Alliance; McKinsey analysis

13 BBC News: Meet the electric pioneers

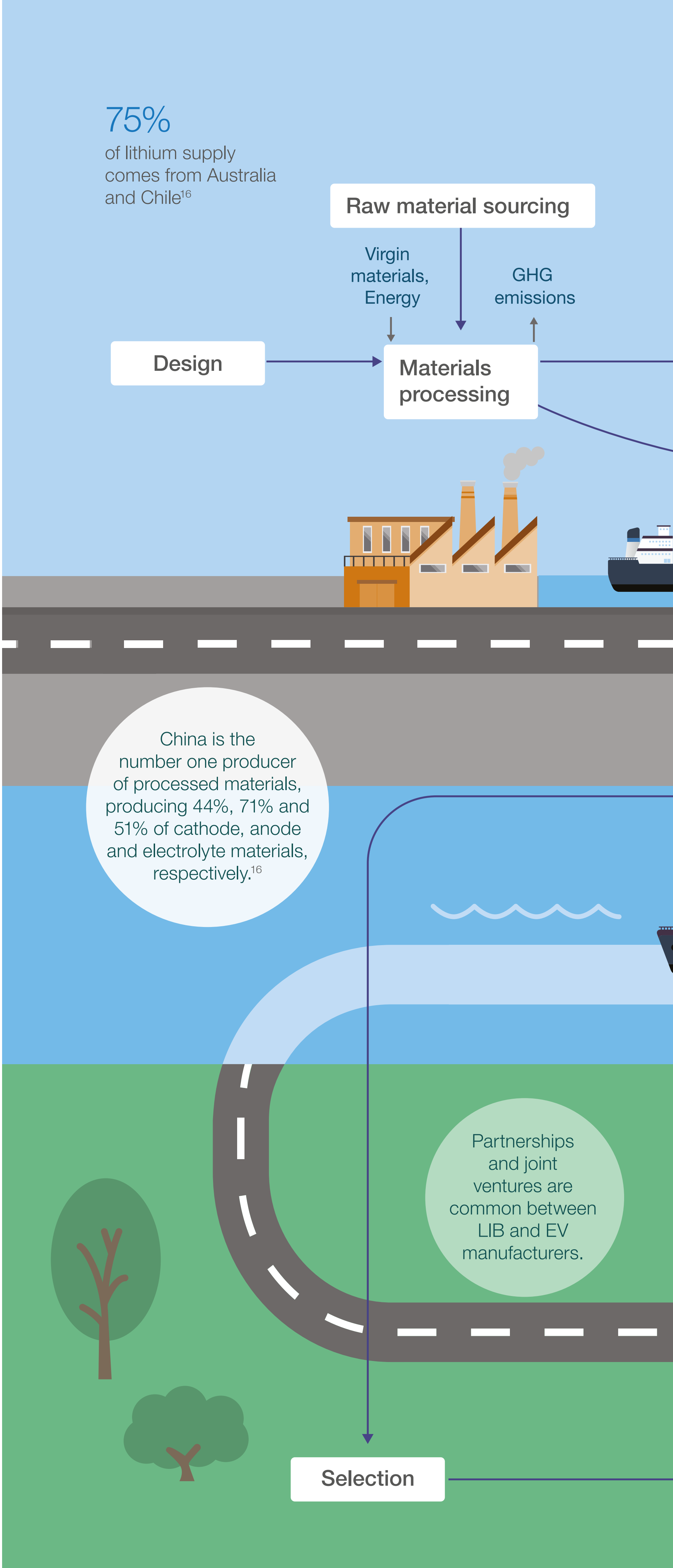
14 International Energy Agency, 2019, *Global EV Outlook 2019*

15 Hornsdale Power Reserve: Strengthening the South Australian Electricity Grid

A linear value chain

The current lifecycle of LIBs generally follows the traditional take-make-dispose model.

There are many negative externalities of this linear supply chain that create serious challenges for the industry moving forward.



16 European Commission, 2019, *Report on the Implementation of the Strategic Action Plan on Batteries*

17 Future Smart Strategies, 2018, *A Lithium Industry in Australia*

18 International Energy Agency, 2020, *Global EV Outlook 2020*

US$11.7bn

Mining concentrate[17]

LITHIUM VALUE CHAIN
2025 FORECAST

50%

of global EV battery manufacturing is in China[18]

US$424bn

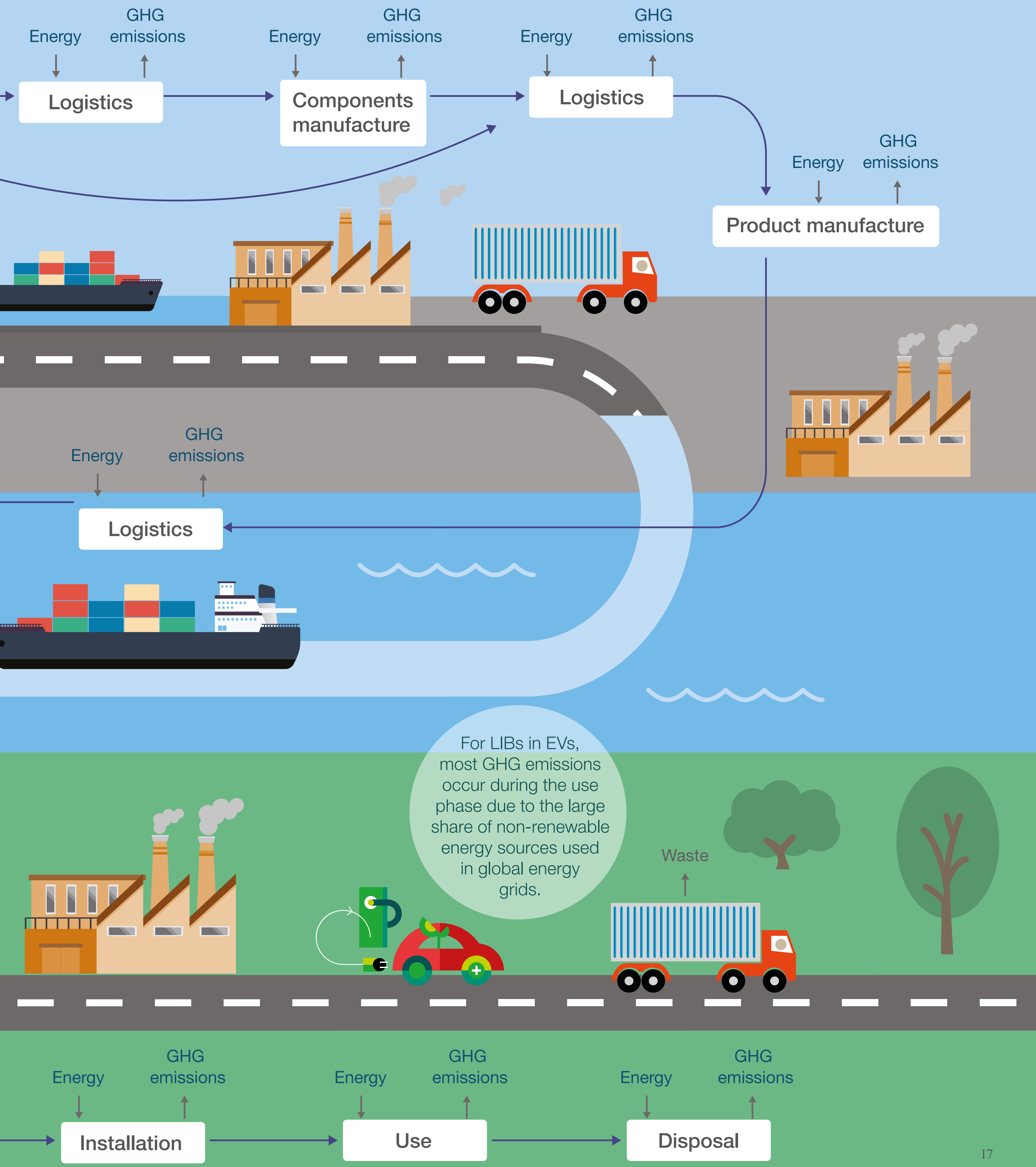
Cell production[17]

LITHIUM VALUE CHAIN
2025 FORECAST

US$1.3tn

Module production[17]

LITHIUM VALUE CHAIN
2025 FORECAST



There are many negative externalities of this linear supply chain that create serious challenges for the industry moving forward.

- **Secure supplies**
- **Embodied energy and carbon**
- **Water consumption and contamination**
- **Labour conditions and community impacts**
- **Lost value**

Secure supplies

There are significant lithium deposits around the world, but limited distribution of lithium wealth.

Lithium is extracted from lithium minerals found in igneous rocks composed of large crystals (spodumene or hard rock) or in water with a high concentration of lithium carbonate (brine). Lithium products derived from brine operations can be used directly in end-markets but require a long production time, while hard rock lithium concentrates must be further processed before they can be used in value-added applications like LIBs.

Today, the world's lithium production is split evenly between hard rock and brine, and can be found in many locations. Despite this, the distribution of lithium wealth – the economic gains from lithium production – is limited to fewer countries. In 2016 this was Chile (52%), China (22%), Argentina (14%) and Australia (10%).[19]

China is a huge importer of lithium resources as it is the main processor and manufacturer of lithium products. It accounts for an estimated 89% of the world's lithium hydroxide,[20] which is required for advanced LIBs with a higher nickel fraction.

Chile, Argentina and Bolivia are thought to have similar levels of lithium resources, though Chile has had a head-start in exporting these resources, predominantly to Asia. While Australia is thought to have fewer lithium resources, it is leading in extraction and export of mineral concentrates.

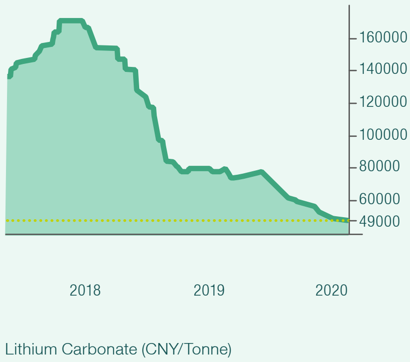


Figure 7: Lithium trading[21]

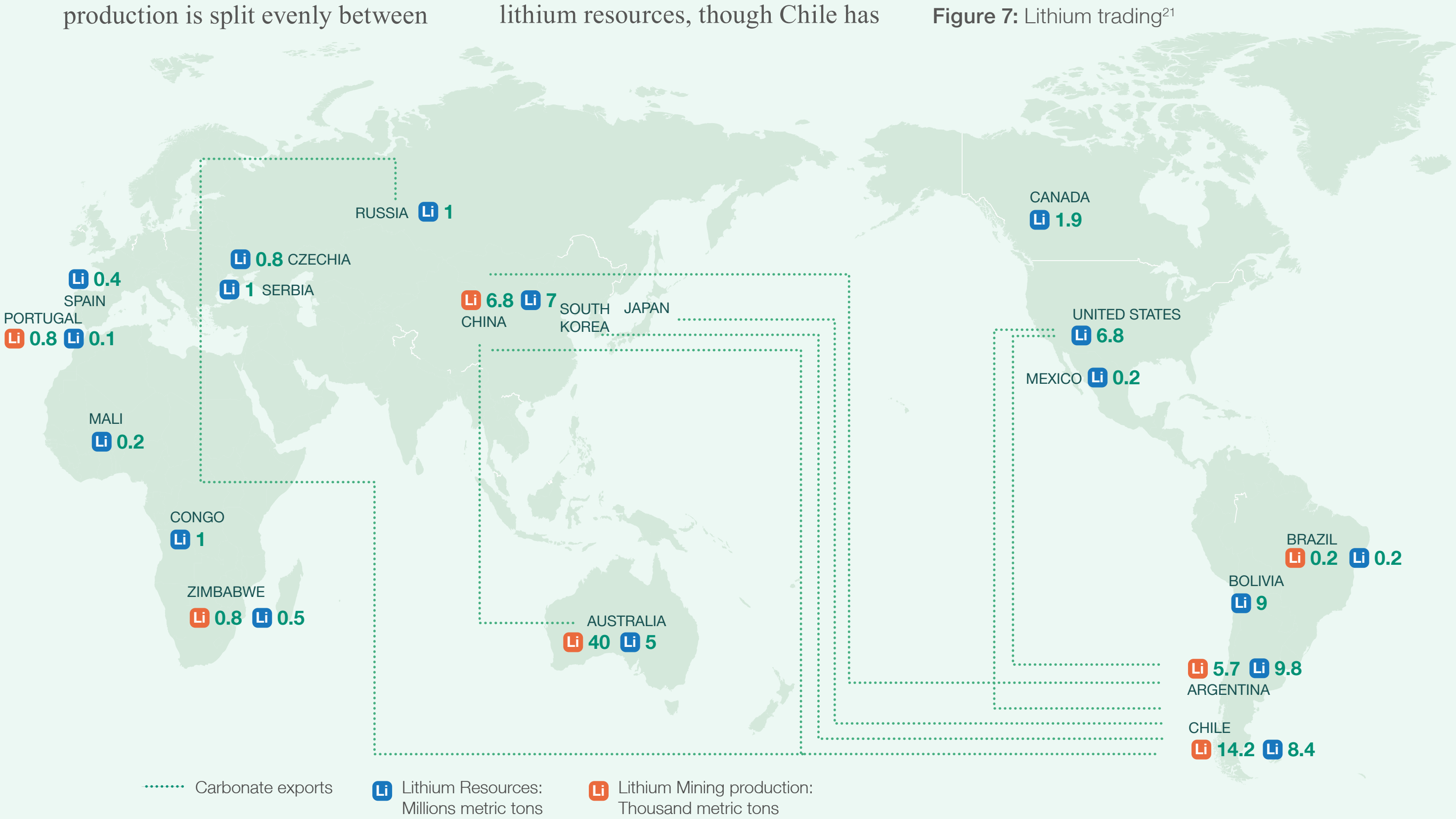


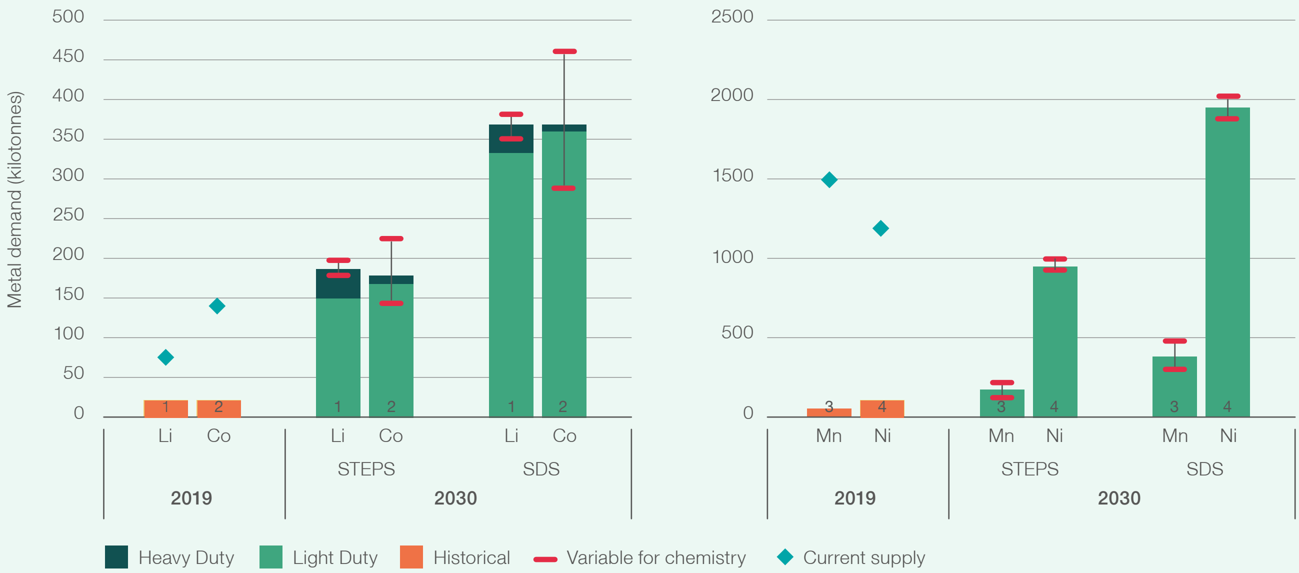
Figure 8: Lithium deposits[22]

19 Swain, 2017, *Recovery and Recycling of Lithium: A review*

20 Australia Unlimited, 2018, *The lithium Ion Battery Value Chain - New Economy Opportunities for Australia*

21 Trading Economics

22 National Geographic



STEPS = Stated Policies Scenario (covers adoption of policies already in place or announced)
SDS = Sustainable Development Scenario (a more ambitious policy context)

Figure 9: Annual demand for lithium [1], cobalt [2], manganese [3] and nickel class 1 [4] batteries from EV deployment, 2019-30.[24]

Global supply and demand of lithium is growing, however demand is outpacing supply.

In 2017, as demand increased, global lithium prices increased to the year's end. This high price and expectations of future demand coupled with the low capital costs of mine operation led to many new entrants to the market.[23] This increased supply has been a factor for the downward trend in price since.

While demand for lithium for non-battery applications such as production of glass, ceramics, greases, lubricants, metal alloys, air conditioning and others will continue to grow steadily, the demand for lithium in EV batteries alone will outstrip current production levels. And as the demand begins to outpace supply, prices are expected to increase again.

The IEA has developed two scenarios for EV uptake that depend on a variety of factors, including policy decisions globally and the projected demand for lithium in 2030 (see Figure 9). The orange bar was demand in 2019 with the blue diamond representing current supply.

Due to the disparity between current supply and future demand, lithium supply security has become a top priority for technology companies. Strategic alliances and joint ventures among technology companies and exploration companies continue to be established to ensure a reliable, diversified supply of lithium for battery suppliers and vehicle manufacturers. Retaining material within the circular economy offers an alternative to the linear supply chain.

Material supply risk goes well beyond lithium.

The choices that are made around cathode battery chemistry affect the demand of metals globally. Issues are arising around scarcity, extraction difficulty and intensity, and transportation. Some materials, like aluminium, plastics and copper, already have large industrial bases and as such have more secure supply chains. Others have more uncertain outlooks.

The European Union (EU) has listed magnesium and cobalt as critical raw materials, meaning they are of high economic importance and high supply risk.[25] Looking at EVs alone, challenges also exist around production volumes of cobalt, manganese and nickel. Demand will outpace supply by 2030, with the difference most dramatic for manganese.

23 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery*
24 Value Chain in 2030 International Energy Agency, 2020, *Global EV Outlook 2020*
25 *European Commission - Critical raw materials*

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Cobalt is classed as a critical metal, which is reflected through its high price. Approximately 70% of cobalt production comes from one country – the Democratic Republic of Congo.[26] In the long term, this is not a significant concern for raw material supply, as it is slowly being phased out of batteries.

Nickel is currently used in many applications and it is anticipated that the demand for nickel in EVs will put pressure on the market, impacting other applications such as stainless-steel production.[26]

As other materials are incorporated in changing chemistries, demand for those materials such as graphite may rapidly increase too.

While production may be able to ramp up to meet demand, there are challenges in rapidly scaling material use. Imbalance in supply and demand is expected along the way and will lead to price spikes, high levels of uncertainty and geographic concentration of production.[27] Recycling has potential to shift some of these dynamics in the long-term. Alternative circular solutions are required in the short term.

The IEA has also identified challenges beyond the sudden ramp-up of production. Environmental impacts – such as local pollution, CO_2 emissions in logistics, and impacts to land, water resources and ecosystems – and social issues – such as child labour and impacts to the wellbeing of local communities.[27]

26 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

27 International Energy Agency, 2019, *Global EV Outlook 2019*

Embodied energy and carbon

Energy used for extraction, processing, manufacturing and delivery of LIBs is known as embodied energy. Similarly, embodied carbon is the carbon emissions (or equivalent) from these upstream processes during material and product development and transportation.

150-200kg CO_2-eq/kWh

The total embodied carbon emissions of LIBs[28]

This is the equivalent to driving a small internal combustion engine vehicle for 1,000km per kWh of battery storage.[29] Based on current emissions during production, the owner of a Tesla Model 3 Standard Range with a 50 kWh battery[30] would need to drive for 50,000km using 100% renewable electricity to offset the embodied emissions of the battery alone.

Cathode material selection

Cathode materials generally require large quantities of energy to manufacture. Cathodes with nickel and cobalt are particularly harmful with the highest potential for environmental impacts, including: global warming, resource depletion, ecological toxicity and human health impacts.[31] These negative impacts could be minimised through the use of alternative chemistries.

Emissions from electricity use should be targeted through increased use of renewables.

One study of LFP, NMC and LMO batteries found that around 40% of total embodied emissions were associated with electricity use. If countries were to transition to clean energy mixes, this 40% contribution could be gradually eliminated.[32]

28 IVL Swedish Environmental Research Institute, 2017, *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*

29 National Greenhouse Accounts Factor 2019

30 Electric Vehicle Data Base

31 United States Environmental Protection Agency, 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion batteries for Electric Vehicles*

32 Yang, Zhou, Zhang, 2017, *GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China*

Water consumption and contamination

"The environmental and occupational health and safety risks related to lithium in brines are comparatively higher than for other sources of lithium, but the potential health effects are currently poorly understood."[33]

Methods to extract lithium are water-intensive and can be environmentally degrading.

For brine deposits, where open evaporation occurs to leave the lithium product, significant volumes of water are lost.[34] These deposits are often in already dry areas, such as the salt flats of Chile and Bolivia.

There is also the possibility of release of lithium into the environment leading to contamination and human health issues. In Tibet, a chemical leak from a lithium mine in 2016 reportedly caused water pollution in the Liqi river, causing damage to the local ecosystem including aquatic life.[35]

33 Agusdinata, Liu, Eakin, Romero, 2018, *Socio-environmental impacts of lithium mineral extraction: Towards a research agenda*
34 Egbue, 2012, *Assessment of Social Impacts of Lithium for Electric Vehicle Batteries*
35 *Wired: Lithium batteries environment impact*

Labour conditions and community impacts

In the pursuit for resource efficiency and value capture, a focus on people and communities should remain front of mind.

The demand for lithium resources has the potential to provide significant social and economic benefits, particularly in countries like Bolivia.

However, concerns that water use is diverted from agricultural needs have been cited in the lithium triangle (Argentina, Bolivia and Chile),[37] as have concerns over access to resources for indigenous populations as well as the general populations.[38] In Chile, public campaigns have included 'Litio para Chile' (Lithium for Chile) and 'Atacama es de todos' (Atacama belongs to everyone), calling for more equitable distribution of resources.[39]

Social lifecycle assessments have highlighted the lack of data around these issues.[40] This is an area where more research is required, with a recent review of lithium mineral extraction identifying a limited focus on social and environmental impacts of the extraction.[41]

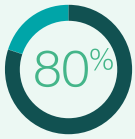
Issues surrounding cobalt supply from the Democratic Republic of Congo have received more attention. A lack of safety equipment and legal protections, alongside child labour, chronic illness and respiratory diseases were documented by Amnesty International, with a report claiming that companies are not carrying out human rights due diligence with international standards.[42] Given the toxicity of metals like cobalt and nickel, high standards are required to minimize the cancer and non-cancer toxicity impact potential.[43]

Initiatives like the *Cobalt Industry Responsible Assessment Framework*[44] are attempting to provide mechanisms for companies to improve visibility, reporting and outcomes in the supply chain.

Of course, social outcomes can vary from supplier to supplier and area to area, which is why social lifecycle assessments need to be tailored to local contexts.

2 million

The estimated number of people employed in the battery value chain



of employees work in developing countries[36]

36 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

37 National Geographic: Lthium is fueling- technology today at what cost

38 Business & Human Rghts Resource Centre: The downside of electromobility

39 pv magazine: Is fair lithium from Chile possible

40 Egbue, 2012, *Assessment of Social Impacts of Lithium for Electric Vehicle Batteries*

41 Agusdinata, Liu, Eakin, Romero, 2018, *Socio-environmental impacts of lithium mineral extraction: Towards a research agenda*

42 Amnesty International, 2017, *Time to Recharge: Corporate Action and Inaction to Tackle Abuses in the Cobalt Supply Chain*

43 United States Environmental Protection Agency, 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion batteries for Electric Vehicles*

44 Cobalt Institute: The cobalt industry responsible assessment framework

Lost value

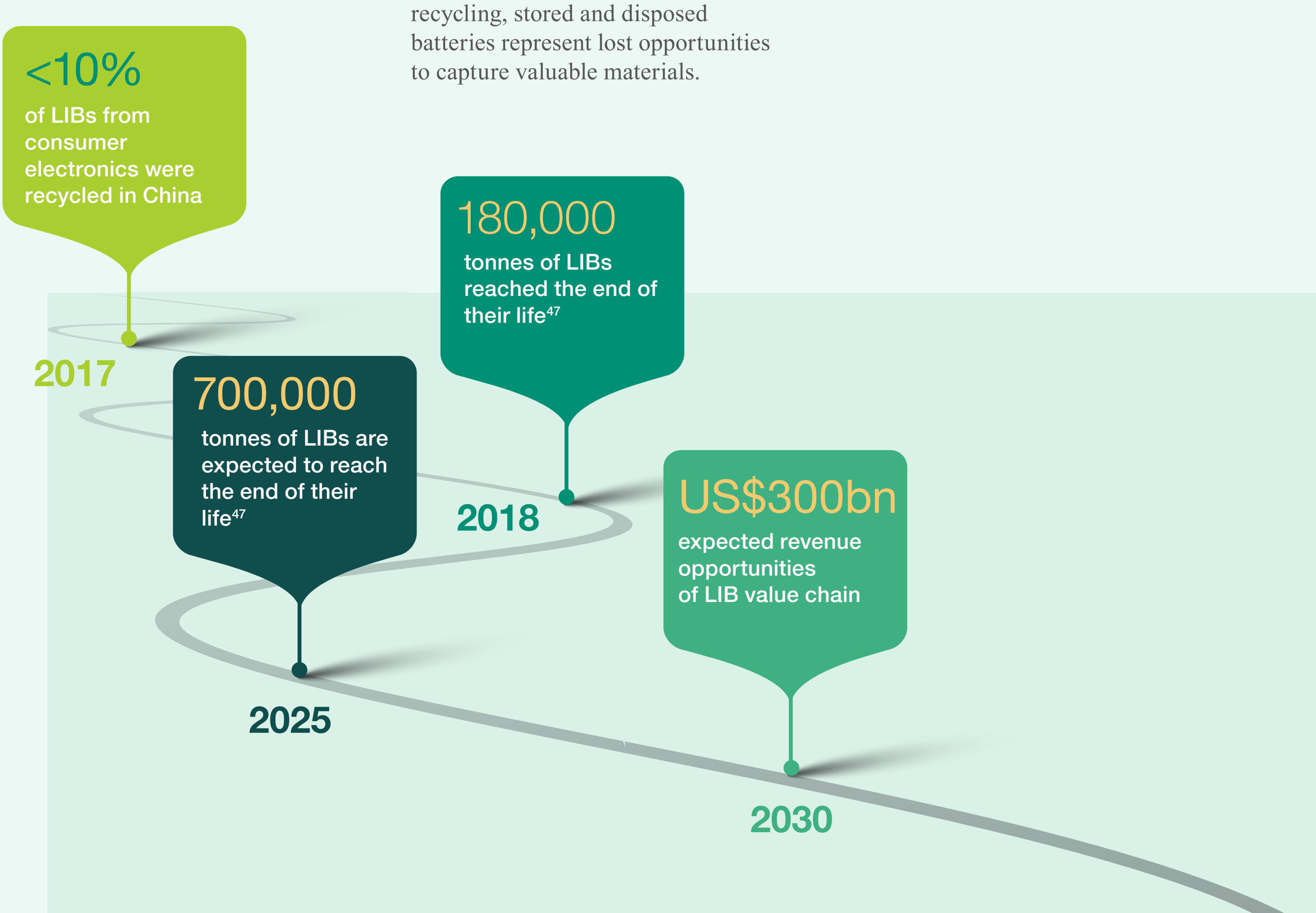
The revenue opportunities of the LIB value chain are expected to be US$300 billion annually by 2030[45] and increasing beyond then. However, to create this opportunity, US$440 billion of investment is required before 2030.

If this investment is not made, then it is likely that much of this valuable material will be lost and the negative externalities realised by the global community. In China, it is estimated that less than 10% of LIBs from consumer electronics were recycled in 2017.[46] The rest went to landfill or remained idle.

Globally, around 50% of LIBs are currently recycled.[47] The other 50% are often stored and/or disposed but not recycled or reused. Following the principles of the waste hierarchy, while reuse is to be promoted above recycling, stored and disposed batteries represent lost opportunities to capture valuable materials.

Efforts are underway globally to recycle material from EOL LIBs, driven by the high relative content and price of cobalt. These measures focus on Lithium-Cobalt Oxide Battery cathode chemistries which have a higher cobalt content. However, the supply stream for these LIBs is still small, making it difficult to achieve economic returns.

The LIB waste issue goes well beyond lost value. Stockpiling, burning and landfilling are not acceptable options for reaching environmental sustainability.



45 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

46 Gu, Guo, Yao, Summers, Widijatmoko, Hall, 2017, *An Investigation of the Current Status of Recycling Spent Lithium-Ion Batteries from Consumer Electronics in China*

47 http://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf

The circular economy presents an opportunity for government, businesses and consumers to rethink the traditional take-make-dispose model of consumption and develop new business models that produce better social, environmental and economic outcomes.

The circular economy represents a shift to an economy where looping back both technical components and biological nutrients into the system replaces typical linear processes

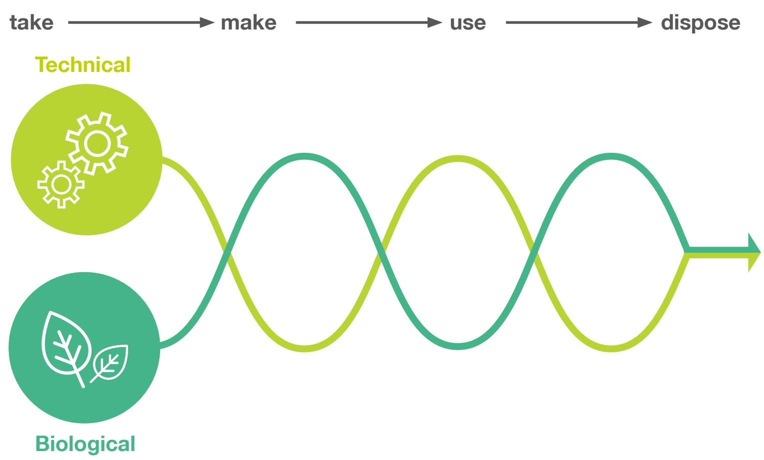
Looking beyond the current take-make-dispose extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources and designing waste out of the system.

Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital. In a circular economy, economic activity builds and rebuilds overall system health. The concept recognizes the importance of the economy working effectively at all scales – for large and small businesses, for organisations and individuals, globally and locally.

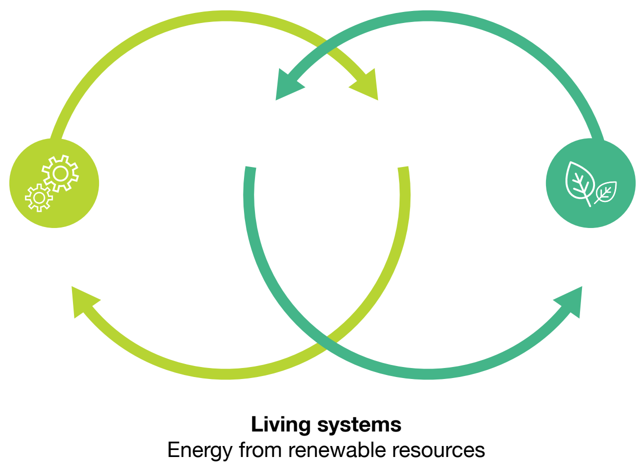
Transitioning to a circular economy amounts to more than adjustments aimed at reducing the negative impacts of the linear economy. It represents a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits. It is based on three principles:

- Keep products and materials in use at their highest possible value
- Regenerate natural systems
- Design out waste and pollution.

Linear economy



Circular economy[48]



48 Arup/EMF Report, adapted from Ellen MacArthur Foundation 2015

The economic potential for individual countries is significant.

For example, building on analysis from the CSIRO in Australia, a circular economy approach to LIBs could save around A$3 billion of materials from leaving the Australian economy every year.

Re-circulating batteries and materials back into the economy will not only avoid losing this value, it will also create additional economic benefits, including:

- Reuse, recovery and recycling industry development
- Jobs creation and skills development in these industries
- Flow on effects in primary industry development, including opportunities for innovation and greater efficiency
- Avoiding negative externalities of mining resources.

The circular economy is on the global agenda

A potential boost of US$4.5 trillion to the global economy by 2030 has been estimated by the EMF.

151 organisations internationally are members, partners or alumni of the Circular Economy 100 – an EMF program that facilitates collaboration, innovation and understanding between members looking to develop CBMs.[49]

In 2018, China and the EU signed a Memorandum of Understanding on Circular Economy Cooperation.[50]

The EMF estimates there is potential for CNY 70 trillion savings for businesses and households by 2040.[51]

49 Ellen MacArthur Foundation, 2018, Member Groups

50 http://ec.europa.eu/environment/circular-economy/pdf/circular_economy_MoU_EN.pdf

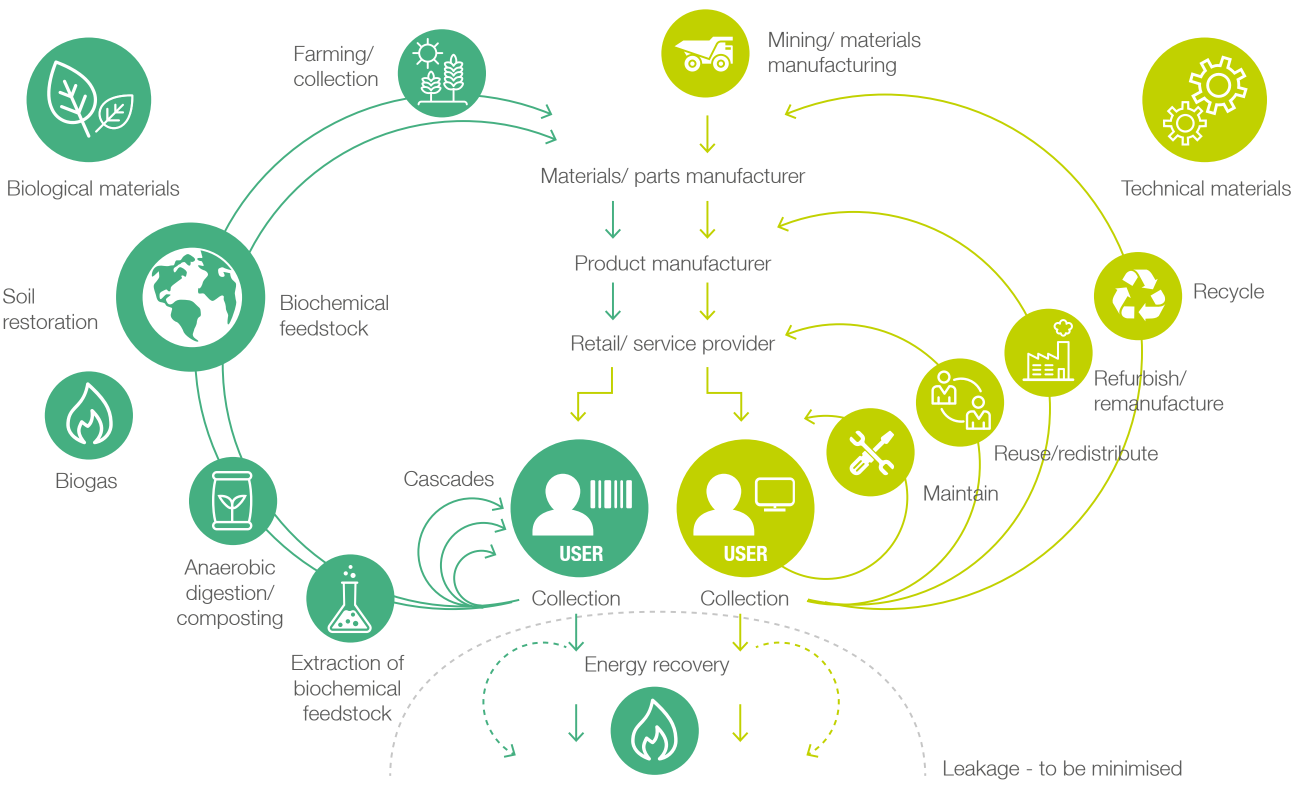
51 Ellen MacArthur Foundation: China Report

Technical and biological cycles

According to the foundational work by the EMF, the circular economy distinguishes between technical and biological cycles. Consumption happens only in biological cycles, where food and biologically-based materials (such as cotton or wood) are designed to feed back into the system through processes like composting and anaerobic digestion. These cycles regenerate living systems, such as soil, which provide renewable resources for the economy.

Technical cycles encompass non-biological materials. In a circular economy approach, the aim is to recover and restore products, components, and materials through strategies like reuse, repair, remanufacture or (in the last resort) recycling.

The world is currently 8.6% circular, according to the Circularity Gap.[53]



Circular economy concept[52]

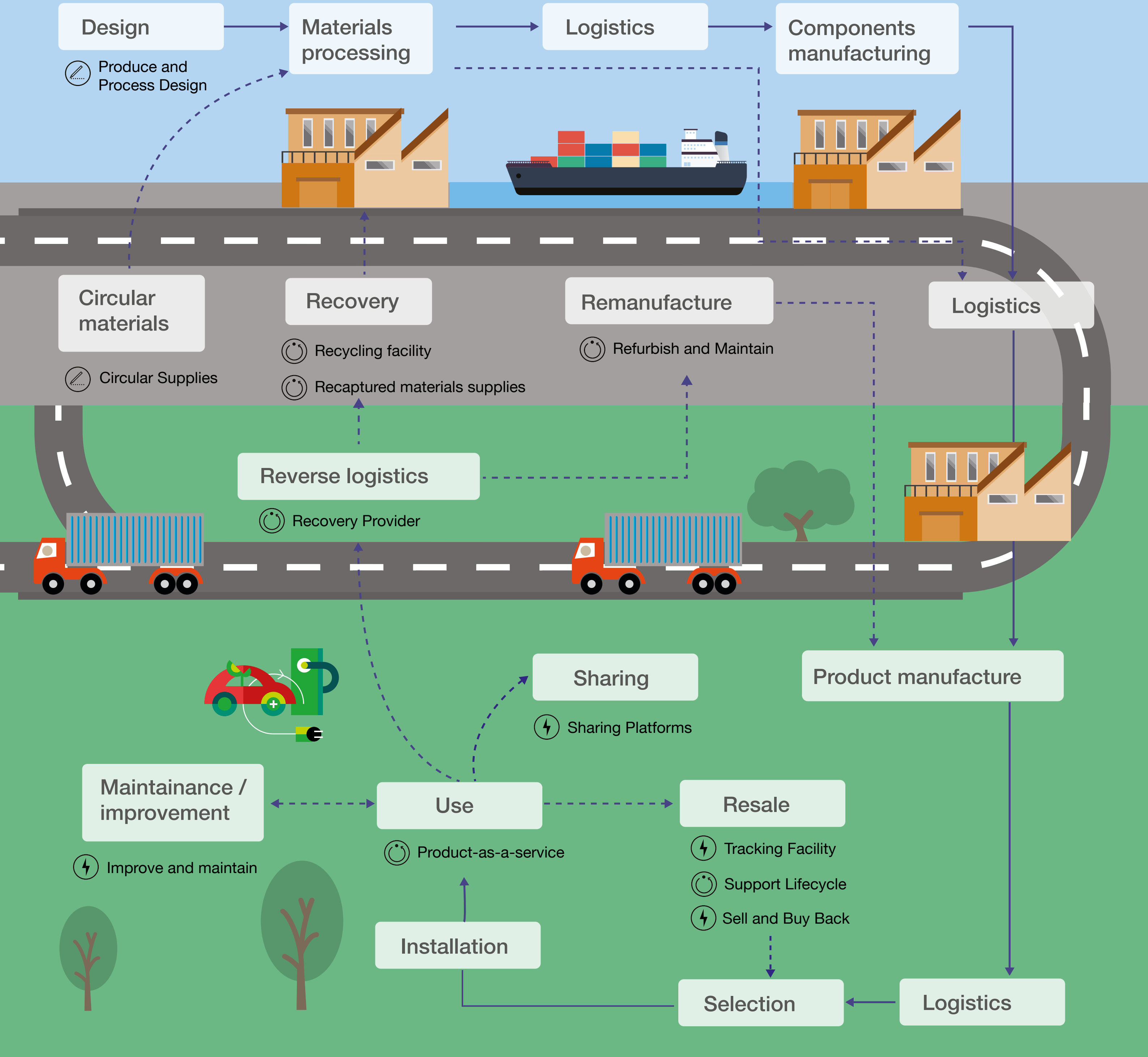
52 www.ellenmacarthurfoundation.org/circular-economy/concept/infographic
53 www.circularity-gap.world/2020

Circular lithium lifecycle

23%
reduction of battery costs with production emissions halved to around 100Mt by 2030

US$22bn
additional value created if 50% of EVs became vehicle-to-grid compatible

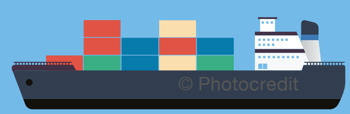
US$70.4bn
anticipated market for mobility-as-a-service by 2030



US$2bn
saved if 61% of EV batteries are reused by 2030

31%
increase in profit if remanufacturing is integrated in LIB supply chain networks

6.5%
of the 2030 demand represents spent batteries



Business models for the circular economy

Several methods of naming and defining CBMs exist. This report explores how seven focus CBMs could apply to the LIB industry globally, covering the whole lifecycle. The seven models are:

CBM1 **Product and process design**
Rethinking the design to improve the maintenance, repair, upgrade, refurbishment and/or manufacturing process.

CBM2 **Circular supplies**
Replacing virgin materials with those sourced from within the circular economy.

CBM3 **Sharing platforms**
Enabling or offering shared use, access or ownership so more people can benefit from the asset.

CBM4 **Product-as-a-service (PaaS)**
Delivering performance rather than products, where the ownership is retained by the service provider.

CBM5 **Lifetime extension**
Extending the service life of products, through engineering solutions or in new applications.

CBM6 **Refurbish and maintain**
Repairing and refurbishing part or whole of the asset so it can be returned to operations or sold at the typical EOL.

CBM7 **Recycling**
Transforming waste into raw materials to return to the circular supply chain.

While there are distinct models, the CBMs do not tend to function individually. Rather they co-exist, co-operate and co-evolve to create a circular ecosystem.

Business models that are based on the circular economy unlock higher value across the whole lifecycle by enabling:

- Greater control of resource streams
- Innovation through the supply chain
- Enhanced collaboration within the supply chain
- Creation of services that capture value.[54]

Importantly, these benefits are maximised and more likely to be simultaneously achieved when all elements of a business model are circular. For example, having a model that focuses only on recycling is theoretically not as economically sustainable as one that focuses on a mixture of models, such as sustainable material development, sharing and reusing platforms, and recycling.

It is not just about dealing with waste, but also reducing total demand and increasing overall efficiency and impact.

54 Carra and Magdani, 2017, *Circular Business Models for the Built Environment*

CBM1
Product and process design

The design of a product or process involves a significant number of decisions, each with implications for the economic, social and environmental impacts of the product.

All CBMs can be influenced by design. This involves rethinking design to improve the maintenance, repair, upgrade, refurbishment and/or manufacturing process.

Research from Yale University indicated that the most effective method to reduce contribution to climate change from LIBs would be to produce the battery cells with electricity from a less carbon intensive energy mix.[57]

Designing a product that makes recycling or disassembly for refurbishment and reuse simpler, and/or creates the opportunity for a new product that can be provided from the material resource contained in the original product.

By adopting some key principles in design, these impacts could be optimised for LIBs. Key strategies include:

– Standardising design both within a design organisation and between organisations

– Designing for repair, modularity, adaptability and disassembly

– Designing out carbon from the production process.

Currently, there is a clear lack of standardisation of battery modules.

EVs can contain cylindrical, prismatic or pouch cells, with different welding techniques, different types of joints, and in either series or parallel. Cells are not designed to be tested and characterised externally. Such testing requires a protocol that is time and cost efficient. Politecnico di Milano is one research institution trying to address the lack of standardisation of battery modules.[55]

Standardised measures relevant to circular design principles could include:

– Standard classification systems such as standardised colour coding of LIBs to communicate type or relevant recycling process

– Standard processes, like efficient removal from EVs.

More broadly, any standardisations that increase the LIBs' ability to be repaired in a routine manner and to be recycled or reused without new R&D occurring, should be adopted. Government has a role in facilitating collaboration for standardisation.

Designing for reuse and disassembly should be a standard design process for LIBs.

Designing for reuse may consider the modularity and replaceability of battery components that have shorter lifespans than other components. Designing for disassembly can also allow individual units, like controllers or cells, to be reused in other applications should the whole LIB unit reach its EOL.

Researchers have identified many challenges in disassembling LIBs. One study examined an Audi Q5 Hybrid System and identified challenges with different screw types and orientations, which required multiple tools and tool changes and difficulty accessing cables and joints. It was determined that partial automation would currently be feasible, however full automation would be complex and expensive.[56]

55 [Interview – Politecnico di Milano].

56 Wegener, Andrew, Raatz, Dröder, Herrman, 2014, *Disassembly of Electric Vehicle Batteries Using the Example of the Audi Q5 Hybrid System*

57 Ellingsen, Majeau-Bettez, Singh, Srivastava, Valøen, Strømman, 2013, *Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack*

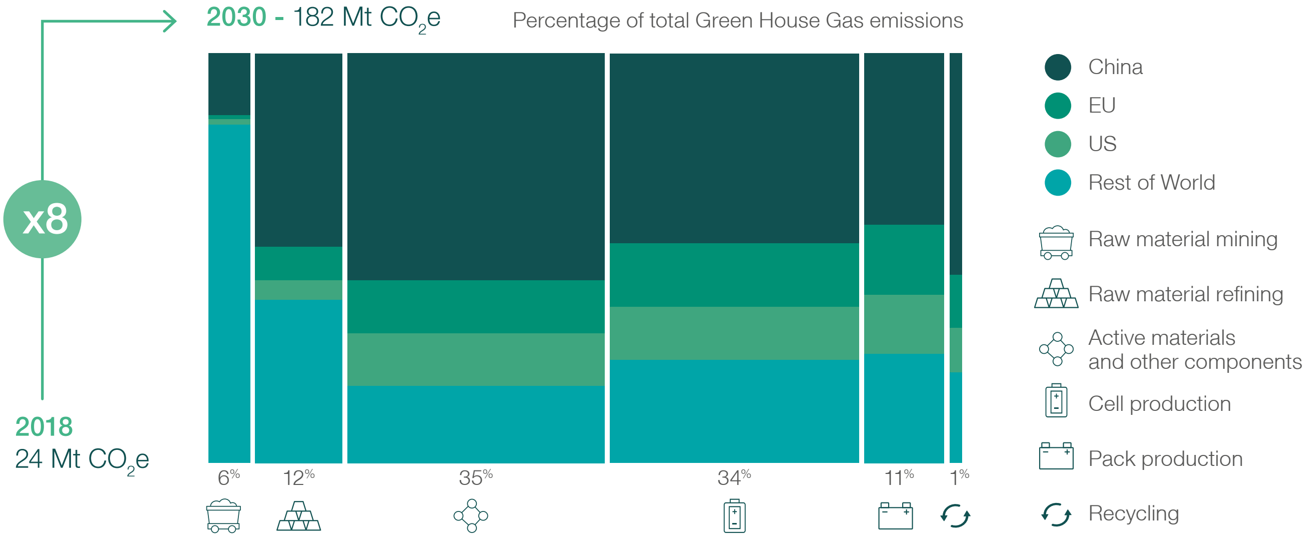


Figure 10: Battery production with significant $C0_2$ footprint, mainly driven by active materials and other components as well as production in China.[58]

General design principles to improve disassembly include:

- Prioritising mechanical connections rather than chemical ones. For example, welding should be avoided. In general, reducing the number of connections would assist
- Minimising the number and complexity of steps to remove and dismantle the LIB
- Using generic tools for disassembly and minimising the number of tools and tool changes required.

Generic connectors can be replaced with ease and are durable. One study recommends:

- Replacing connections with snap-fitting mechanisms
- Using discrete components, not deformed: bundler, spring, screw, bolt, nut, lock washer[59]

Designing out emissions is key to reducing the impacts of battery production.

Analysis from the World Economic Forum (WEF) examining the 2018 and (projected) 2030 carbon footprint of LIBs showed:

- The significant CO_2 footprint of the middle of the supply chain
- The active materials and other components, and cell production
- The influence China has on these emissions, even more so in the short-term.

Promisingly, the WEF estimates in its projections that production emissions from LIBs in 2030 could easily be halved to around 100 Mt at negative cost, and therefore reduce battery costs by 23% while reducing associated emissions. This is only a base case and so there is opportunity to design out more carbon.

Important design-related levers to achieve this include:

- Improving process efficiency. This covers a broad range of improvements relevant to general manufacturing processes and those specific to LIBs, such as using a solvent-less process in battery manufacturing to reduce energy requirements[60]
- Utilising renewables. This covers electrifying production processes and vehicles using renewable energy sources
- Improving LIB chemistry. This covers improvements in materials efficiency and energy density (for example by shifting chemistries from NMC622 to NMC811). This abatement is particularly attractive from an economic perspective.

58 World Economic Forum, Global Battery Alliance, McKinsey analysis

59 Peiró, Ardente, Mathieux, 2017, *Design for Disassembly Criteria in EU Product Policies for a More Circular Economy*

60 United States Environmental Protection Agency, 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion batteries for Electric Vehicles*

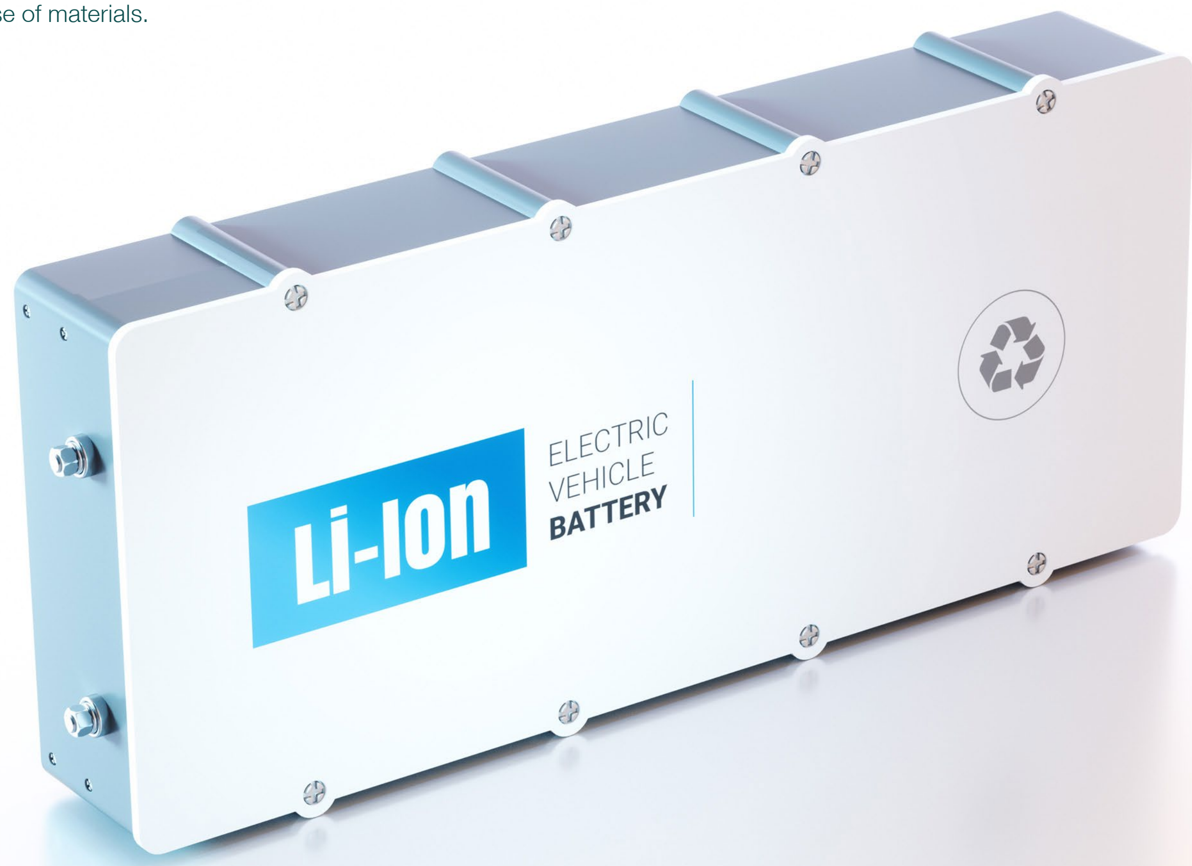
Design opportunities include:

Modularity. Currently, when the number of cells in a battery system is increased, the number of control systems increases accordingly. If one control system could be adapted to control a number of batteries, this would lead to more efficient use of materials.

Synergy in component life span. The lifespan of the control system (15 years) tends to be shorter than that of the batteries (20 years). Increasing this could prevent premature EOL.

Reducing embodied emissions by designing LIBs and processes to reduce embodied carbon, embodied energy and the use of hazardous and non-recyclable materials.

Increasing standardisation by developing and utilising standardised hierarchies, classification systems and processes.



Designing for disassembly through prioritising mechanical connections and sharing documentation on how to disassemble products

Reducing use of undesirable materials. Research and design could reduce cobalt and nickel to increase resilience of supply chain and reduce environmental impacts.

Reducing share of metals by mass to reduce environmental and health impacts.[61]

Incorporating recovered materials by utilising recovered materials.
(see CBM 2: Circular Supplies and CBM 7: Recycling Facility)

61 United States Environmental Protection Agency, 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion batteries for Electric Vehicles*

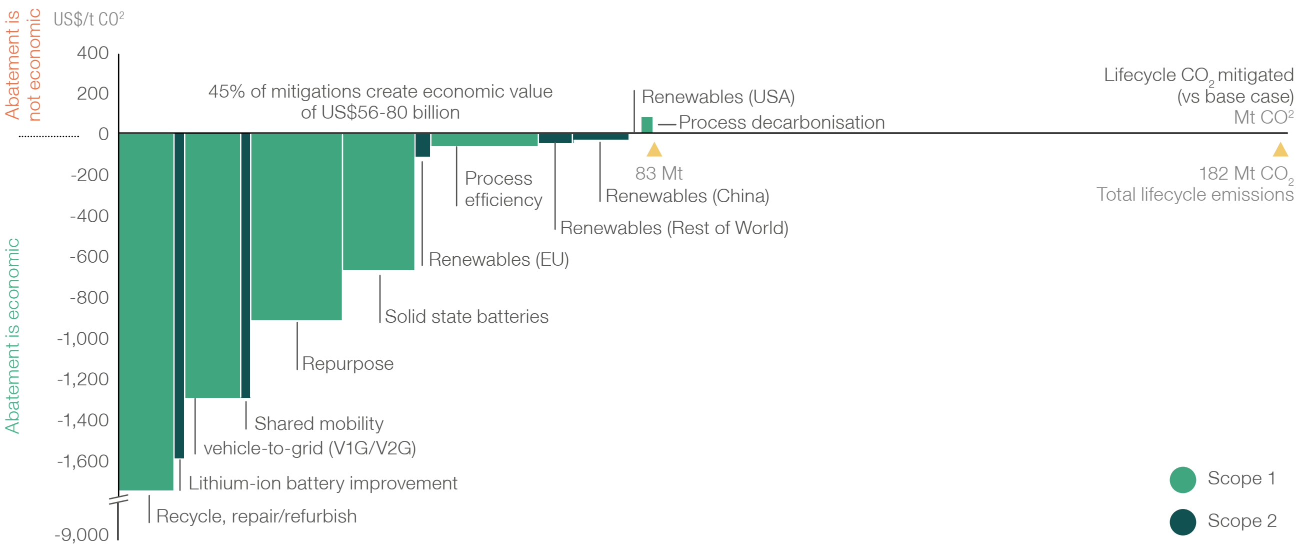


Figure 11: Relative costs of CO_2 mitigation (vs. base case).[62]

The responsibility for circular design sits largely with China, the EU and the US, as by 2030, they will be designing and producing the most LIBs.

As such, they should lead efforts to collaborate on circular design. Other countries can encourage them to establish goals, design priorities and collaborations required for better product and process design by opting for products from manufacturers/ countries which adopt circular design principles.

CASE STUDY

The EU

The European Commission is currently leading in this space. The latest EU Circular Economy Action Plan (March 2020) identifies electronics and ICT, and batteries and vehicles as key project value chains. It sets actions related to legislative and non-legislative measures and aims to lead global efforts on circular economy.

The upcoming Ecodesign Working Plan will be critical to continuing developments in Europe and further afield.[63]

62 World Economic Forum, Global Battery Alliance, McKinsey and SYSTEMIQ analysis

63 *European Commission: A new Circular Economy Action Plan*

Benefits

- Addressing the issue upfront makes all later lifecycle stages
- Reduction in material, finance, energy and emissions
- Changes to design can be implemented immediately

Barriers

- Pace and competitiveness of R&D makes circular design a low priority
- Lack of motivation from manufacturers as many benefits are realised later in the supply chain
- Lack of interaction between designers and recyclers
- Lack of design standardisation between designers
- High and urgent demand for batteries
- Lower market acceptance or understanding of reused or recycled products

Future enablers

- **Legislated incentives** to encourage manufacturers to close the loop on their supply chain and prepare for battery EOL. This includes procurement policies to encourage recycled content
- **Target percentages** for recycled and non-hazardous materials
- **Design for disassembly principles** which will provide guidance on how to design for a more efficient deconstruction phase that can constantly evolve
- **Labelling or materials passports** that track and disclose material origin and composition, recyclability and repair process. Global databases on LIB contents, recycling and repair instructions would accompany this tracking
- **Standardising** design by industry and government to enable more efficient recycling and to allow the waste industry to plan for future waste streams
- The European Commission's new Circular Economy Action Plan[64] will play an important leadership role

64 European Commission, 2020, *EUR-Lex - Access to European Union Law*

CBM2
Circular supplies

This involves replacing virgin materials with those sourced from within the circular economy.

It is important that designers rethink their material procurement to include reverse logistics, supply ownership models, and reclaim and recycling schemes.

Virgin aluminium and raw electrode materials are key drivers of greenhouse gas production in the materials sourcing phase, with aluminium representing up to a quarter of the greenhouse gas emissions from battery manufacturing. By swapping to recycled aluminium, the energy inputs to produce aluminium can be reduced by around 95%.[65]

This is important beyond carbon footprint reduction. A circular economy will look to chemistries to provide the basis of innovative products made from renewable or recovered feedstocks that are designed to be reused, recycled, or the feedstock renewed through natural processes.

There are several circular supply chains to replace those linear ones.

Materials from reserve logistics and recovery schemes along with recycled, recyclable, upcycled and non-hazardous substances should be selected where possible. Partnerships, R&D, and pilot programs will enable trust and economies of scale to be achieved for the materials market.

There are several supporting activities that could help facilitate the move towards circular supplies. These include:

- Reverse logistics
- Suppliers' ownership models for production of components
- Product reclaim schemes
- Mandatory reporting initiatives.

Companies are emerging that capture lithium from existing applications, such as Lithium Australia, which is producing high-performance battery cells made using lithium recovered from mine waste and spent LIBs.[66] *See CBM 7: Recycling Facility for more information on capturing materials.*

The social outcomes of supply chains need to be considered alongside the environmental ones too.

Product design should consider the security and ethics of supply chains. Following guidance, such as the *Due Diligence Guidance for Responsible Mineral Supply Chains*[67] from the OECD, should be mandated.

Government has a strong role to play in influencing procurement through:

- Guidelines for public and private procurement to demonstrate best practice
- Targets for circular supplies to enhance market confidence and growth
- Legislated restrictions and targets to increase enforceability
- Early procurement of new circular materials to demonstrate viability.

65 International Energy Agency, 2020, Global EV Outlook 2020

66 Lithium Australia, 2020, LIT converts waste into high performance LIB cathodes

67 OECD Due Diligence Guidance for Responsible Supply Chains

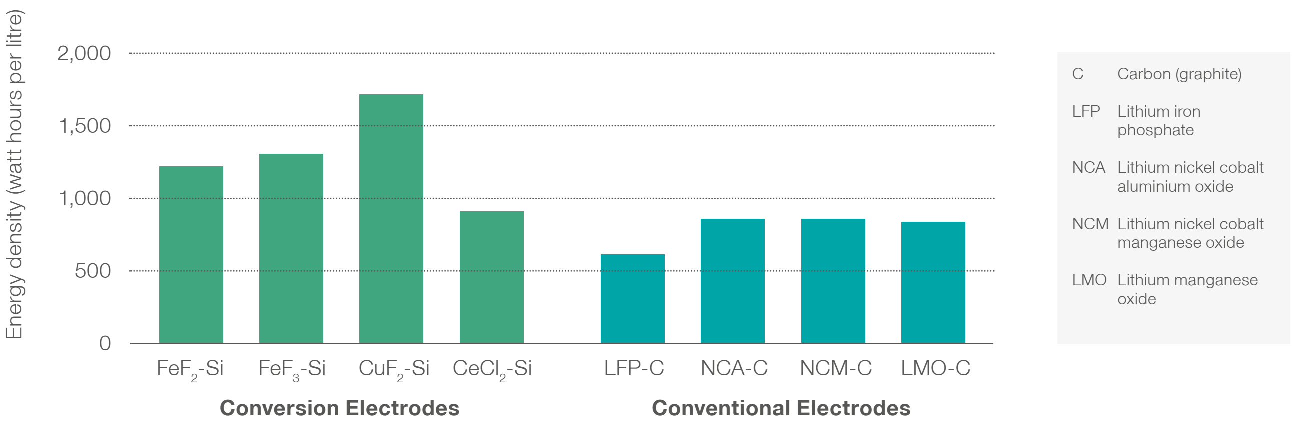


Figure 12: Batteries that use conversion electrodes can store more energy in a given unit stack volume than those using conventional electrodes.[68]

Alternative electrode chemistries should be selected with care.

There is still significant uncertainty around which cathode chemistries will dominate in the coming decades. This uncertainty presents an opportunity to lock in chemistries that optimise social, environmental and economic outcomes.

There are many promising candidates under research. An example is batteries that use 'conversion materials' such as copper or iron fluorides and silicon. These are more common materials with secure supply chains, that demonstrate energy storage can be increased significantly (see Figure 12).[68]

While it is unclear which chemistries will prevail, ensuring that materials are efficient, scalable and have low environmental impact should be a priority of R&D activities. The sooner these new generation materials are adopted by industry, the sooner the waste industry can gain certainty of battery composition and invest in appropriate recycling technologies.

Benefits

- Supply chain materials and visibility
- Reduction in materials, finance, energy and emissions

Barriers

- Lack of transparency
- Increasing level of demand for lithium, increasing pressure on production
- Uncertainty over future battery chemistries
- Low volume of EOL lithium for recycling
- Uncertainty or lack of data around performance, life span and operational costs

Future enablers

- **Legislated incentives** to encourage manufacturers to close the loop on their supply chain. This includes procurement policies to encourage recycled content
- **Target percentages** for recycled and non-hazardous materials
- **Labelling or materials passports** that track and disclose material origin and composition
- **Standardised LIB chemistry** to enable the waste industry to plan for future waste streams

68 Turchenjuk, Bondarev, Singhal, Yushin, 2018, *Nature: Ten years left to redesign lithium-ion batteries*

CBM3
Sharing platforms

This involves enabling or offering shared use, access or ownership so more people can benefit from the product.

LIBs are already enabling the transition to a low-carbon economy by supporting the renewable energy industry. Through sharing platforms, their role could be magnified by increasing the availability of existing LIBs.

Stationary LIBs can be shared through initiatives such as community battery projects, where community members share a larger scale battery instead of smaller individual storage units.

This type of centralised battery storage can utilise resources in operation, management and maintenance more efficiently than in smaller disaggregated units.

For those who own an EV, there are ways to optimise its use for the grid during idle time through vehicle-to-grid (V2G) applications.

V2G applications reduce emissions and costs for consumers and energy networks, and can reduce the need for additional storage.

VG1	VG2
Smart charging of batteries when grid demand is low, reducing peak demand in the grid.	Using batteries during idle time to support the grid and participate in power markets.
Benefits:	**Benefits:**
Reduces capacity required of grid	Improves the business case for EVs
User pays lower fees for energy from grid.	Increases storage capacity and resilience of grid.

Table 1: Vehicle-to-grid applications

Globally, if 50% of EVs were enabled to be V2G compatible through offsetting the need for additional storage, 17 Mt of carbon emissions would be saved each year and US$22 billion of additional value would be created.[69]

V1G/V2G solutions could lower costs for electric vehicle charging infrastructure by up to 90%.[70]

69 World Economic Forum: A vision for a sustainable battery value chain in 2030

70 IRENA, 2019, *Innovation Outlook: Smart Charging for Electric Vehicles*

There are several other ways in which batteries can be shared. In general, these occur through sharing the technology the batteries are used to power, rather than the batteries themselves.

Car sharing, whereby users share a vehicle owned by someone else,[71] is an important example. This could increase or decrease the demand for EVs. The WEF target is that 16% of all passenger cars sold in 2030 are in shared arrangements, creating 3 Mt of CO_2 savings due to reduced battery demand.

While sharing models can make LIBs more accessible and increase their use, there is also the potential to increase the total amount of waste produced as more LIBs may be demanded overall.

So while the transition to more sustainable forms of transport and energy storage is to be encouraged, it is important that the whole value chain transitions to circular thinking. This CBM highlights the need to ensure the correct ownership structures and responsibility attributions are in place.

Benefits

- Increase utilisation rates
- Decrease unnecessary demand for new LIBs
- Maximise the benefits of LIBs
- Increased access to affordable mobility
- Cost savings associated with smart grid interactions
- New services increase long term revenues

Barriers

- Preference of consumers to have individual ownership rather than shared or no ownership
- Software and legislation required to enable
- A shift from upfront investment to ongoing payments has potential implications for operating capital and taxation
- Payback period is often greater, which influences the kinds of loans required

Future enablers

- **Pilot projects and investment** in scaling-up these projects. Many digital and hardware-based platforms are emerging, and rapid scale is expected soon. Funding and investment are important for this. Both EVs and grids have to be ready
- **Regulation** that enables integration of EV storage as a energy resource within the grid

71 Farenden, Lee-Williams (Arup), 2019, *The Future of Mobility and MAAS: Governance and Orchestration*

CBM4
Product-as-a-service

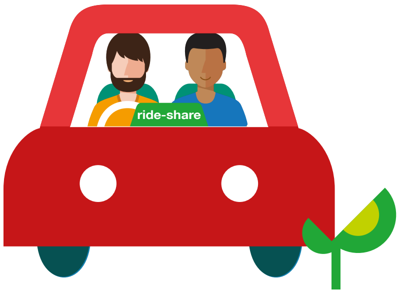
This involves delivering performance rather than products, where the ownership is retained by the service provider.

There are a number of different PaaS business models that can be applied to LIBs and use LIB applications, including pay-per-service unit (that is, mobility-as-a-service or MaaS), product leasing, product renting or deposit and loan schemes.

In considering EVs, ride-sharing applications are key examples of the rise of demand-responsive transport services. MaaS models look at integrating multiple transport modes – cars, buses, both public and private – into one service by one transport service provider.[72]

It is critical that services such as these provide sustainable transport options for their users. Non-ownership business models enable a centralised business to maintain control of a vehicle, and therefore responsibility of its performance, maintenance and utilisation.

The owner is incentivised to seek optimised use and life, as the longer and better the asset performs, the better it is for the owner. This business is also responsible for the repair, reuse or EOL of the batteries.




© Kynny/istock

72 Farenden, Lee-Williams (Arup), 2019, *The Future of Mobility and MAAS: Governance and Orchestration*

Leasing is another way to provide a PaaS that EV manufacturers are engaging in. Renault Group has an EV battery leasing model. It owns the largest stock of EV batteries in the world (180,000 at the time of interview). This enables Renault Group to control and optimise the battery lifecycle while making EVs more affordable. LIBs for powering warehouses, or EVs for the construction industry (such as forklifts), are also becoming more readily available.

Deposit and loan schemes are an extension of the idea of leasing. This would see users pay a deposit on a battery, or battery powered product, that the user loans for a fee. When out of date, the user can then upgrade the product for a lower than outright purchase and the deposit is only lost if the battery is not eventually returned.

As with sharing platforms, these business models must overcome the emotional and status benefits of owning rather than renting.[73]

The MaaS market is anticipated to be worth US$70.4bn by 2030.[74]

Benefits

- Increased utilisation rates
- Accessibility due to low capital investment for users
- Centralised responsibility for maintenance, repairs and recovery
- Potential slowing in demand of EVs
- Increased long term revenues from new services

Barriers

- Lack of normative behaviours from consumers towards leasing rather than owning
- Low awareness of PaaS models
- A shift from upfront investment to ongoing payments has potential implications for operating capital and taxation
- Payback period is often greater which influences the kinds of loans required
- Consumer preference for new individual products, rather than shared or service-based products

Future enablers

- **Regulatory support** for EVs and autonomous vehicles
- **Selection of EVs** by ride-share and taxi services
- Governments and private industry **developing and promoting PaaS models**
- Academia and incubators focusing on **creating innovative PaaS** business models

73 Lewandowski, 2015, *Review of Designing the Business Models for Circular Economy - Towards the conceptual framework*

74 Markets and markets: Mobility as a service

CBM5
Lifetime extension

This involves extending the service life of the product, through engineering solutions or in new applications.

The WEF estimated that if 61% of EV batteries were re-used, 20 GWh of ESS would be avoided, saving 1 Mt of CO_2 and US$2 billion in 2030, increasing in the long-term.

While warranty is typically for 5 years (e.g. Tesla and Nissan) the residual capacity after 8 years of life is often above 80%.[78]

The lifecycle assessment of LIBs shows the significant emissions during production phase.[75] If the lifetime of the battery can be increased, then more benefit can be realised to offset these embedded emissions. Optimised operation and use of the battery, or battery materials, can significantly reduce the need for production, which causes environmental externalities.

In an EV, the power requirements for a LIB are high. During the automotive service life, LIBs must meet rapidly fluctuating demands for acceleration and deceleration that depend on the vehicle's driver.

Currently, EV manufacturers like Renault state that the capacity of current EV batteries is expected to reduce to 75% capacity after 8-10 years. At this point they are no longer appropriate for use in EVs. The residual capacity after use in EVs is between 60% and 80%.[76]

By optimising when and how the battery is charged and discharged, the LIB life can be extended. A simple measure to extend the lifetime is to keep the level of charge within 30% and 80%,[77] as opposed to draining the battery and fully charging it each time. However, the biggest extensions in lifetime are gained from secondary use of the LIB.

There is great potential for LIBs to be shifted from high performance, compact use cases to lower performance use cases in their second life where performance per unit of weight or volume is less important.

Second life applications in less extreme environments are a significant opportunity.[79] In the second use the fluctuation in energy demand and charge is smaller, which helps the battery to maintain its energy storage capacity longer. Additionally, when the batteries are used in stationary applications, they can be stored more easily, optimising climate control.

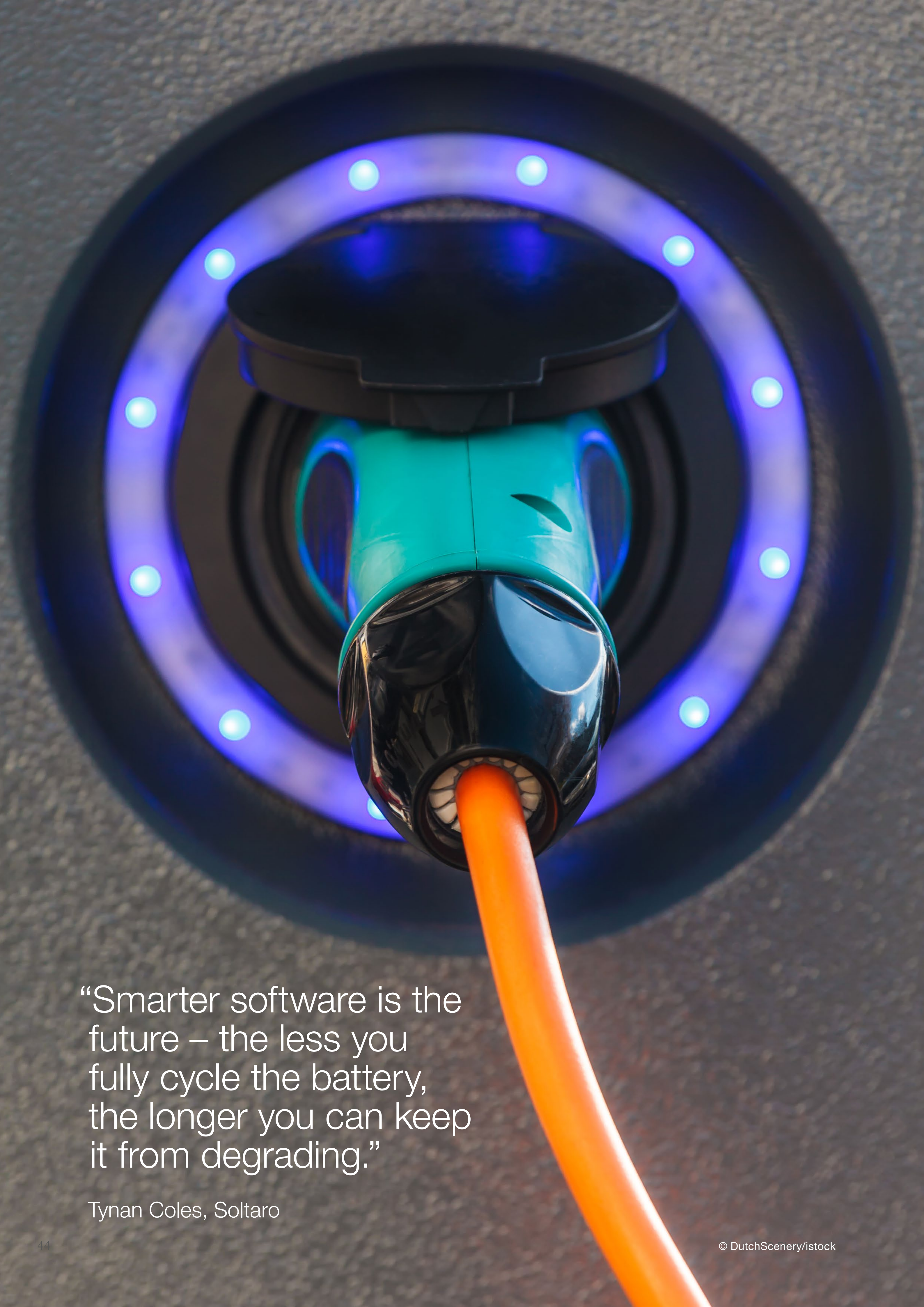
75 Gaines 2012; Sullivan and Gaines 2012; Zackrisson et al. 2010

76 Bobba, Mathieux, Blengini, 2019, *How Will Second-Use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-Ion Batteries*

77 #easyelectriclife Groupe Renault: What is the lifespan of an electric car battery

78 E-MOB: Circular Economy strategies for end of life e-mobility batteries

79 Olsson, Fallahi, Schnurr, Diener, van Loon, 2018, *Circular Business Models for Extended EV Battery Life*



"Smarter software is the future – the less you fully cycle the battery, the longer you can keep it from degrading."

Tynan Coles, Soltaro

Some examples of second-life applications after use in EVs include:

– Utility-scale storage, which will have reduced environmental impact if combined with PV[80]

– China's biggest operator of telecomms has begun to use second-life LIBs instead of lead acid batteries for back-up power[81]

– Use in buildings – residential, office or industrial applications with no space constraints.

For example, the Johan Cruyff Arena in Amsterdam in The Netherlands, is a multi-purpose stadium with 590 battery packs – 340 new and 250 second-life LIBs that are certified to last 10 years. These batteries enable them to avoid peak demand power.[81]

There will be significant volumes of LIBs available for second life by 2025, as demonstrated in Figure 13. Most will be in China.[82]

Batteries may need to undergo repair or refurbishment at the end of their life, to enable alternative uses. This is discussed in *CBM 6: Refurbish and maintain*.

The use of products in second, third, or more applications is called cascading use. Research has indicated that it could be preferable to follow a more 'open' style of circularity with EV LIBs by cascading their use into alternative functions, rather than reusing LIBs in their original EV application.[83]

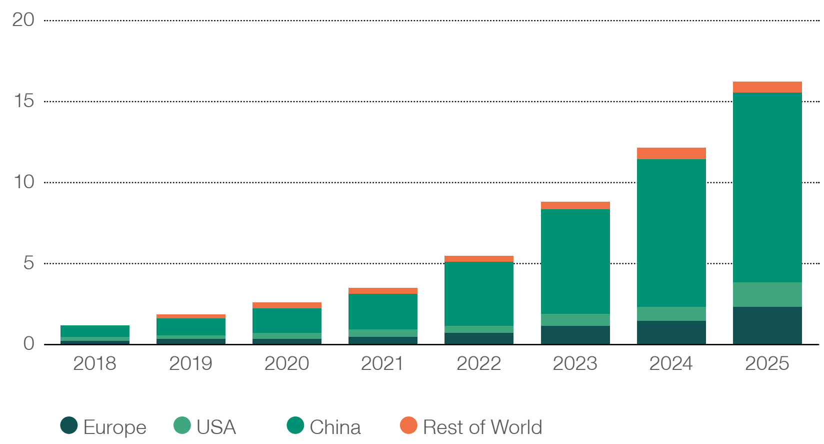


Figure 13: Lithium-ion batteries available for second life by geography GWh)[81]

However, there are remaining challenges in implementing cascading use. Testing the state-of-health (SoH) and certification of batteries is needed but can be time consuming; it is not standardised and requires availability of data on the batteries. Electrochemical Impedance Spectroscopy is a current method for testing battery performance, but it has long testing times that may not be compatible with high volumes and rapid turnover of batteries.

Research at the Politecnico di Milano is attempting to address the lack of standardisation in battery modules, which would assist in developing more standard testing protocols.[84] A single market for the second life of batteries would help address the challenges of logistics,[85] by increasing standardisation, awareness and accessibility.

80 Ioakimidis, Murillo-Marrodán, Bagheri, Thomas, Genikomsakis, 2019, *Lifecycle Assessment of a Lithium-ion Phosphate Electric Vehicle Battery in Second Life Application Scenarios*

81 Pagliaro, Meneguzzo, 2019, *Lithium battery reusing and recycling: A circular economy insight*

82 Melin, E.; 2018, *The lithium-ion battery end-of-life market*

83 Richa, Babbitt, Gaustad, 2017, *Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy*

84 [Interview – Politecnico].

85 [Interview – Renault Group]

CASE STUDY

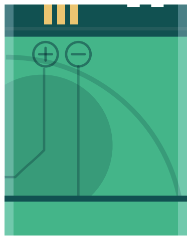
Renault's Advanced Battery Storage Program

The Program is aiming to build the biggest stationary energy storage system using EV batteries in Europe at 70 MW/60 MWh,[86] leading the push for large-scale second-life applications.

Renault Group is also developing a SoH protocol for EV batteries.[87] Key points include:

- If the battery is over a performance threshold, it can go on for a second life
- Temperature remains the biggest influencing factor for the SoH, followed by speed of charging
- Consideration included for providing a certified warranty.

Nissan Leaf is also exploring batteries used in stationary energy storage systems (SESS) in Tumeshima, Japan.



Renault recovers almost 100% of batteries that no longer meet automobile requirements.[88]

© Monty Rakusen/Cultura

86 E-*Mob: Circular economy strategies for end-of-life e-mobility batteries*

87 [Interview – Renault Group].

88 #easyelectriclife.Groupe.Renault; *A European agreement in favour of the circular economy of the battery*

CASE STUDY

CIRC-eV

Politecnico di Milano has recently supported the development of a new Interdepartmental Laboratory, called CIRC-eV, looking to develop and test new circular solutions for the reuse and recycling of LIBs. Its program of work covers:

- Utilising vision systems, databases for module classification and robotic mechanical arms for disassembly
- Following disassembly, developing protocols for:
  - reassembly for specific second-life application, if sufficient residual capacity
  - recovery of materials
- Mechanical pre-treatment of waste before chemical recovery process
- Replicable methods for certifying the residual capacity of cells, including data analytics to reduce testing time and forecast useful life.

Benefits

- Increase utilisation of batteries
- Extending the useful life of LIBs thus reducing demand for new LIBs

Barriers

- SoH testing processes are complicated and costly
- Concerns over performance and safety
- Lack of standardised process to classify batteries for re-use
- High demand for cobalt and lithium to be recirculated into market rather than left in use[89]
- Refurbished or repaired batteries have to compete with newer, more efficient battery technologies

Future enablers

- **Collection systems** that adequately consider the safety issues of battery storage
- **Testing and certification of batteries,** enabling them to be eligible for new applications. Technology to quickly determine the performance of the battery will facilitate this
- **Materials/product passports or labels** to quickly provide information on the battery
- **A single market for second-hand batteries** to increase standardisation, awareness and accessibility
- **Pilots and R&D** on second-life software and optimisation

89 Bobba, Mathieux, Blengini, 2019, *How Will Second-Use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-Ion Batteries*

CBM6
Refurbish and maintain

This involves repairing and refurbishing part or whole of the product so it can be returned to operations or sold at the typical EOL.

This may involve repairing LIBs, reusing parts of LIBs for new batteries or other applications, and refurbishing LIBs to restore performance.

Repair is made difficult by the current design and manufacturing processes used for LIBs (see *CBM1: Product and process design*). The feasibility of this CBM is largely determined by actions in the design phase. By following principles of design for disassembly, refurbishment and repair, the costs of this model are reduced.

In the WEF's *Vision for a Sustainable Battery Value Chain in 2030*, the effect of increasing repair of fault batteries from 80% to 95% is estimated to retain 30 GWh of battery capacity. This equates to 2 Mt of carbon emissions and US$2 billion saved in 2030.[90]

Among other EOL strategies is the remanufacturing of batteries for reuse in the EV or lower performance applications. Remanufacturing is generally seen as the most environmentally friendly EOL option for a product.[91] It returns a used product to like-new condition with a warranty for the buyer and is a well-known practice in the auto industry where almost 80% of components are remanufactured.

Automotive product remanufacturing accounts for two thirds of all remanufacturing and is a US$53 billion industry in the US and more than US$100 billion worldwide.[91] Remanufacturing has its strongest tradition in the auto industry where EVs are the newest lines of products.

To develop processes for the remanufacturing, it is important to have a good understanding on how the battery degrades to the point at which its capacity is not sufficient for EV use.

LIBs at the end of their life can have their electrochemical performance regained through refunctionalisation of their cathodes. Electrochemical and chemical lithiation methods can be used to return batteries to 'original capacity'. This results in a 50% decrease in embodied energy, compared to cathode production from virgin materials.[92]

Remanufacturing products for their original application through methods like this could provide significant environmental and economic benefits.

A recent study showed that up to a 31% increase in profit can be achieved if remanufacturing is integrated in LIB supply chain networks.[93]

A challenge of remanufacturing is the uncertainty around cathode chemistries, given changing research and preferences. This challenge may highlight the need for government intervention. Remanufacturers' profits are expected to be lower than the original manufacturers and therefore the use of incentives to promote remanufacturing have been suggested.[94]

90 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

91 Gutowski, Sahiul, Boustani, Graves, 2011, *Remanufacturing and Energy Savings*

92 Ganter, Landi, Babbitt, Anctil, Guastad, 2014, *Cathode Refunctionalisation as a Lithium-Ion Battery Recycling Alternative*

93 Li, Dababneh, Zheo, 2018, *Cost-Effective Supply Chain for Electric Vehicle Battery Remanufacturing*

94 Gu, Ieromonachou, Zhou, Tseng, 2017, *Optimising Quantity of Manufacturing and Remanufacturing in an Electric Vehicle Battery Closed-Loop Supply Chain*

CASE STUDY

Relectrify

Relectrify is a start-up based in Australia that is enabling second-life applications. Its solution is software-based and enables batteries to be controlled on a more granular basis.

Second-life batteries have a spread of performance and they are often limited by the weakest cell. By improving battery control systems, they are offering improved resilience to individual cell or module collapse, reduced testing needs, improved safety and cycle life, and other benefits which improve performance and costs.

Relectrify is looking for collaborations with battery manufacturers, integrators and automotive companies.

Benefits

- Increase utilisation of batteries
- Can sell parts cheaply to other places, where there may be people for whom the technology is less accessible
- Extending the useful life of LIBs thus reducing demand for new LIBs
- Avoid costs of new LIBs

Barriers

- Uncertainty over future dominant chemistries
- Lack of motivation of battery and EV designers to design for repair, refurbishment or disassembly
- Determining the faults and performance of batteries through SoH testing
- Concerns over performance and safety
- Lack of a standardised process to classify batteries for re-use
- Refurbished or repaired batteries have to compete with newer, more efficient battery technologies
- High demand for cobalt and lithium to be recirculated into market, therefore preference to recycle rather than reuse[95]
- Uncertainty over EV battery performance in stationary applications

Future enablers

- **Collection systems** implemented by recovery providers to enable efficient logistics in the supply chain
- **Testing and certification of batteries** that would enable them to be eligible for new applications. Technology to quickly determine the performance of the battery will facilitate this
- **Materials/product passports or labels** to quickly provide information on the battery
- **Government incentives** to support commerciality gap of remanufacturing operations due to changing battery chemistry
- **Design for repair, refurbishment and disassembly**
- **Industrial symbiosis**[96] or collaboration between traditionally separate industries

95 Bobba, Mathieux, Blengini, 2019, *How Will Second-Use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-Ion Batteries*

96 Mathur, Deng, Singh, Yih, Sutherland, 2019, *Evaluating the Environmental Benefits of Implementing Industrial Symbiosis to Used Electric Vehicle Batteries*

“Recycling old batteries and manufacturing waste could provide an economic advantage.”

Zarko Meseldzija, American Manganese Inc.

CBM7
Recycling facility

This involves waste being transformed into raw materials to return to the circular supply chain.

In 2030, based on current policies, the number of spent batteries would represent around 6.5% of the 2030 demand.[97]

Battery recycling can provide 13% of the global battery demand for cobalt, 5% of nickel and 9% of lithium in 2030.[98]

In Australia, the value of recoverable metals from the 138,000 tonnes of LIB waste anticipated in 2036 is estimated to be between A$813 million and A$3.09 billion.[99]

Already, some materials are being recovered from LIBs.

Today there are commercial-scale LIB recyclers in several European countries, the US, Canada, South Korea, Japan, China and in a few other nations. The high value of cobalt is the current driver for recycling LIBs,[100] alongside nickel and copper.[101] In many cases, not all materials are recovered as the recyclers focus on these metals. The use of cobalt in LIBs is being reduced over time so this incentive will diminish.

Envirostream, a subsidiary of Lithium Australia (which has published patents for a hydrometallurgical recovery process), has successfully conducted a series of recycling trials for EV battery packs and expects to ramp up recycling operations.[102]

There are advantages and disadvantages associated with certain recycling methods, and the lifecycle impacts of these methods depends on several factors.

The two most prominent recycling methods are pyrometallurgy (utilising high temperatures) and hydrometallurgy (utilising aqueous solutions). These are sometimes used in combination, and with mechanical separation.

Pyrometallurgical methods are applicable to the greatest number of battery designs, which is important given uncertainty over future dominant chemistries, though they do not provide as much economic efficiency as hydrometallurgical methods.

Newer methods are emerging that offer additional efficiency and recovery, though their performance at the commercial scale is less well understood.[103]

The lifecycle impacts of pyrometallurgical and hydrometallurgical methods have been studied. One review found that hydrometallurgical processes recovered more materials than pyrometallurgical processes on average, and identified broad impacts for each, as well as landfill:

- *Pyrometallurgy:* the largest impacts are caused by plastic incineration and electricity generation, causing global warming, human toxicity and terrestrial ecotoxicity potential
- *Hydrometallurgy:* the largest impacts are caused by electricity generation and landfilling residues, causing global warming, human toxicity and terrestrial ecotoxicity potential.[101, 104]

97 International Energy Agency, 2020, *Global EV Outlook 2020*

98 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

99 CSIRO, 2018, *Lithium Battery Recycling in Australia*

100 Heelan et al, 2016, *Current and Prospective Li-Ion Battery Recycling and Recovery Processes*

101 Boyden, Soo, Doolan, 2016, *The Environmental Impacts of Recycling Portable Lithium-Ion Batteries*

102 Waste Management Review, 2020, *Envirostream to- recycle spent EV- batteries*

103 Hendrickson, Kavvada, Shah, Sathre, Scown, 2015, *Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California*

104 Mathur, Deng, Singh, Yih, Sutherland, 2019, *Evaluating the Environmental Benefits of Implementing Industrial Symbiosis to Used Electric Vehicle Batteries*

Comparing the impacts of different batteries and recycling methods will provide varying results in different contexts, since the extent of impacts are so dependent on battery design and chemicals, location (and therefore transport), usage patterns and sources of energy utilised in the supply chain.

One study on hydrometallurgy recovered cobalt, nickel and lithium products at over 99.5% purity and manganese over 90% purity.[105]

In the same study, transport was found to have a significant influence. For example, transporting batteries from Australia to Europe was found to increase the global warming potential by 45% for pyrometallurgical processes and the human toxicity potential by 550% for hydrometallurgical processes.[106]

There are a number of emerging opportunities such as bio-leaching,[107] and pre-recycling steps such as mechanical shredding and size-based sorting[108] and pre-sorting of cathodes[105] that can improve recycling system efficiency.

Regardless of the exact solution, recycling is considered an important activity for more sustainable outcomes, particularly by reducing resource depletion and reducing air emissions.[107]

There are several challenges of recycling that need to be addressed:

- There are many available chemistries, designs and manufacturing methods. Therefore, standardisation and designing for recyclability will help improve recycling rates, in addition to an increase in the flexibility and variety of recycling facilities.
- Uncertainty regarding future dominant chemistries will have an influence over the most appropriate method, whether certain methods become obsolete, and the viability of recycling, especially if more valuable materials such as cobalt are phased out [107, 108]
- Cost of recycling processes are currently too high, as are logistics and testing of batteries which occur before recycling. SoH testing is slow and costly, so decisions on whether to reuse, repair or recycle are slow *(refer to CBM 5: Lifetime extension and CBM 6: Refurbish and maintain)*
- Lack of information and standardisation when it comes to disassembly
- Downcycling can occur, whereby the purity of materials produced can be low and so applications for recycled materials are reduced
- There is only an emerging understanding of the risks of recycling processes for LIBs. There are physical and human health hazards via air emissions, water use and contamination, especially in emerging economies. These risks can vary depending on location, technologies, processes and mitigations
- Safety concerns as EOL LIBs are categorised differently across the world, as general solid waste or hazardous or universal waste. Categorisation as hazardous or universal waste would mitigate safety risks – such as spontaneous combustion or release of hazardous chemicals in landfill[108] though the price of logistics would necessarily rise
- Reducing complexity of logistics should be addressed alongside other challenges, and careful thought should be given to balancing safety and performance with travel distances and legislation rigidity.

105 Chen, Ho, 2018, *Recovery of Valuable Metals from Lithium-Ion Batteries NMC Cathode Waste Materials by Hydrometallurgical Methods*
106 Boyden, Soo, Doolan, 2016, *The Environmental Impacts of Recycling Portable Lithium-Ion Batteries*
107 Ordoñez, Gego, Girard, 2015, *Processes and Technologies for the Recycling and Recovery of Spent Lithium-Ion Batteries*
108 Wang, Gaustad, Babbitt, 2015, *Targeting High Value Metals in Lithium-Ion Battery Recycling Via Shredding and Size-Based Separation*

The ultimate goal is to address these challenges while creating a recycling industry that is:

Flexible, considering how requirements may change over the coming decades

Standardised, to enable greater information sharing and efficiency during deconstruction and recycling.

Given the importance of LIB composition and design, the more information recyclers have about the materials of a given battery, the better able they are to process it. For this reason, telemetry and materials passports will likely play a key role in the future recycling industry.

CASE STUDY

Lead-acid batteries

In 2018, demand for lead-acid batteries (LABs) was 450 GWh and demand is expected to stay steady over the coming decade.

Lessons can be learned from the EOL treatment of LABs.

In many countries, the environmental impact of these batteries has been significant. Lead exposure and lead release into the environment are consequences of below standard facilities. However, in Europe and North America, the approach has had more success. They have been able to implement point-of-sale return systems that have closed loops up to 99%. Tight regulations are in place to protect worker safety and the environment.[109]

109 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

Micro-recycling and decentralisation

While the world tends towards globalisation and macro-scale recycling, it can be a challenge for areas with lower population densities and slower uptake of EVs to keep up with global leaders. In Australia, large distances between cities and neighbouring countries makes logistics expensive, and the uptake of EVs has lagged behind other western countries. This gives Australia time to learn from other regions and implement solutions later.

Countries facing these challenges are looking for alternative solutions. Compelling research is being completed that focuses on micro-recycling at the local scale.

This research is being led by Australia where Professor Veena Sahajwalla and the SMaRT Center is running the *ARC Industrial Transformation Hub for Micro-recycling of Battery and Consumer Wastes*, funded by the Australian Research Council.[110]

The project is focused on developing Australia's advanced manufacturing capability, utilising high-temperature reactions and selective synthesis techniques to create valuable products including metallic alloys, oxides and carbon. These products will feed into both local and global supply chains.

Micro-recycling is anticipated to be a significant enabler for countries like Australia where distances are large and volume is small, relative to areas like the EU. This process of decentralisation could also develop manufacturing skills and jobs in rural centres and cities alike.

Benefits

- Reduces raw material demand and captures current lost value of used materials
- Job creation for waste collectors, pre-treatment companies, waste managers, waste processers and researchers
- Environmental impact of EOL controlled and reduced
- High potential for revenue creation, especially through rare earth metals
- Opportunity for further innovation and development of recycling processes and products

Barriers

- Unclear allocation of responsibility and cost
- Magnitude of cost and responsibility of logistics
- Lack of standardisation for waste collection, regulation, hazardous materials and approvals
- Insufficient standardisation of battery design
- Need to balance local, decentralised solutions with the efficiency and scale of centralised operations
- Investment to develop appropriate infrastructure

Future enablers

- **Clear and standardised rules** for collection, repair, resale and recycling[111]
- **R&D** into key topics such as improving the quality of recycled materials
- **Extended Producer Responsibility** schemes
- **Design for disassembly,** including **information sharing** of disassembly guidelines and creation of **materials passports**
- **Taxes or tariffs** on imported batteries that can fund EOL activities
- **Best practice guidelines**

110 UNSW Sydney: Smart centers new ARC industrial transformation hub microrecycling battery and consumer wastes

111 Huang, Pan, Su, An, 2018, *Recycling of Lithium-Ion Batteries: Recent advances and perspectives*

The storage, treatment, disassembly, recovery, recycling, disposal, and management of the processes comes at a cost. The matter of who pays these costs, and when, is critical.

Government?

This approach ultimately makes the community, which does not necessarily directly cause nor benefit from correcting the externality, indirectly responsible for bearing the costs.

Consumers?

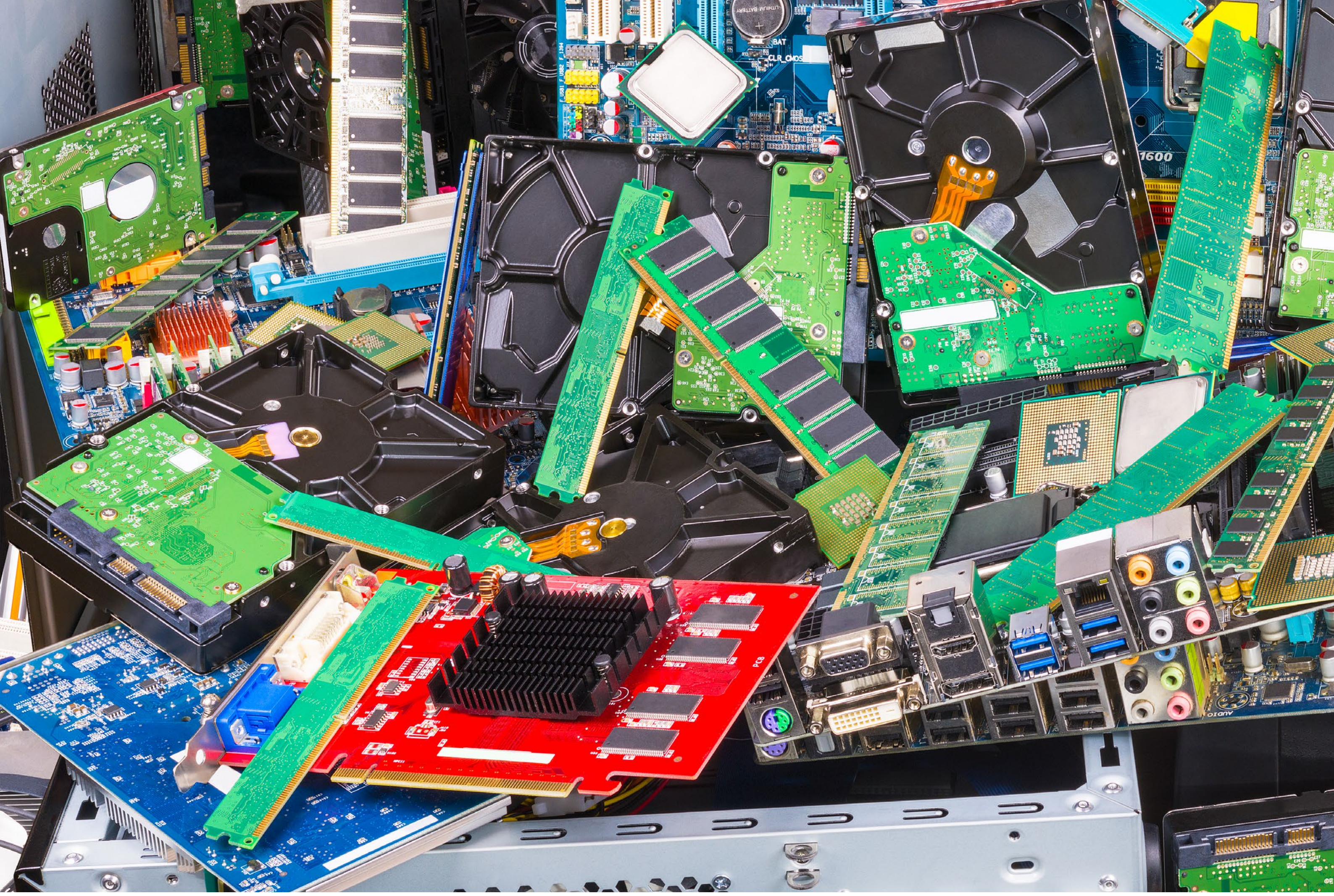
This is a common approach that could be implemented at alternative EOL cycles – either at the start as an upfront recycling fee or at the end as a disposal fee.

Producers?

This would fall under an Extended Producer Responsibility (EPR) principle.

...and when?

Funding for recycling could be before or after use.



CASE STUDY

Regulation in the EU

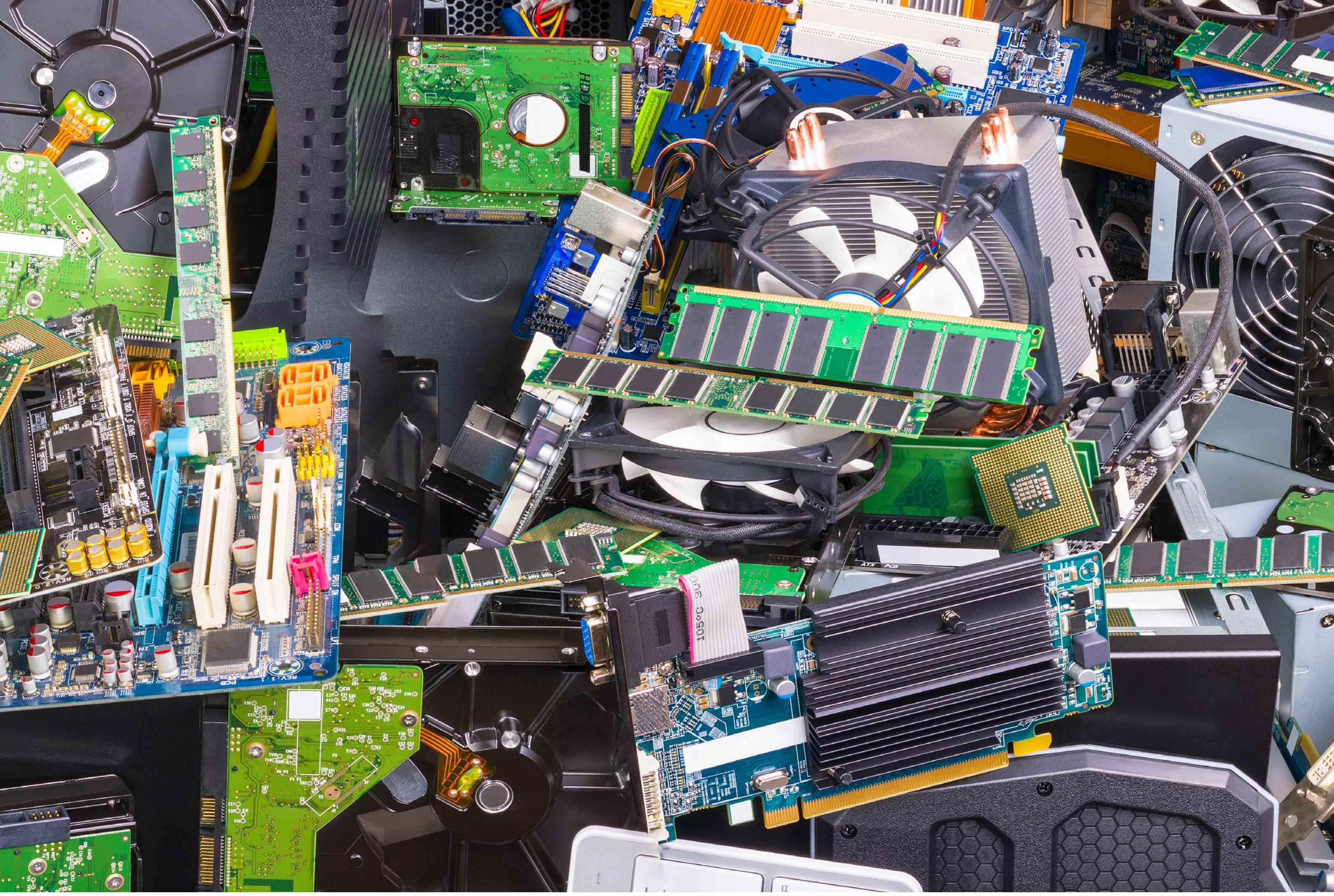
In the EU, the pay-as-you-go approach provides a good case study and has proven to be more cost-effective.

In the EU, the Waste Electrical and Electronic Equipment (WEEE) Directive relies on the EPR principle, whereby producers are responsible for waste regardless of their location. In addition, the Directive outlines:

- Recovery and recycling targets including weight recovery quota, ramped up over time
- E-waste requirements outlining how to handle waste in order to protect the environment and human health
- Allocated responsibilities for financing, reporting and information
- List of wastes including common nomenclature, terminology, coding and classification
- Registration of modules and specific labelling required.

When it comes to EVs specifically, End-of-Vehicle directives require the automakers to take extended responsibility for their vehicles and components after use (EU/Directive 2000/53EC, ELV).

Under the extended responsibility, automakers are financially or physically responsible for their vehicles at the end of their lifecycles. This new responsibility requires that automakers either take back their products with the aim of reusing, recycling, or remanufacturing, or delegate this responsibility to a third party.



The Batteries Directive 2006/66/EC is extending the product life of batteries as a waste prevention measure, through better re-use, or providing used batteries with a second life, which fully complies with circular economy principles:

- A circular economy keeps the added value in products for as long as possible and eliminates waste
- Member States shall take measures to promote re-use activities and the extension of the life span of products, provided the quality and safety of products are not compromised, by encouraging the establishment and support of recognised re-use networks and by incentivising remanufacturing, refurbishment and repurposing of products.

From numerous contacts, presentations and congresses, it seems that the priorities of the legislator regarding batteries is now evolving into the direction of:

- Extension of the product's service life
- Re-use and second life
- Use of recycled components and materials.

In the EU, the Strategic Action Plan for Batteries[112] in Europe was adopted in May 2018. It brings together a set of measures to support national, regional and industrial efforts to build a battery value chain in Europe, embracing raw material extraction, sourcing and processing, battery materials, cell production, battery systems, as well as reuse and recycling. In combination with the leverage offered by its market size, it seeks to attract investment and establish Europe as a player in the battery industry.

112 European Commission: ANNEX 2 – Strategic Action Plan on Batteries

With the industry on the cusp of exponential growth in the uptake of LIBs globally, policy makers, industry and investors need to work together to establish the policy, technology and business models that enable a circular economy for the industry.

Policymakers

Policymakers should foster a supportive regulatory, research and business environment for circular business models locally and internationally.

Recommendations

Implement product stewardship schemes to allocate responsibility for LIB components and materials

Develop financial incentives and use policy levers to spur demand for circular solutions

Work with industry and other governments to facilitate standardisation where appropriate

"It's important we do this early so it's not an issue."

Joyanne Manning
Arup (Australasian Resource and Waste Leader)

Product stewardship

Product stewardship allocates responsibility to either those who design, produce, sell or consume a product for minimising the product's environmental impact. The design of product stewardship schemes, including EOL, is a key issue and should be a priority for countries without stewardships schemes.

The WEEE Directive in the EU has been a leader in this area and can provide key lessons for other regions and countries. Mandatory schemes have greater potential for impact, however, they need to be considered in the context in which they occur and developed collaboratively with industry to ensure they are fit-for-purpose.

Incentives and levers

Government-led change and support for industry help provide the necessary shift to the circular economy mindset. Typical interventions include:

- Education, information and awareness raising campaigns
- Collaboration platforms (public-private partnerships, R&D programs, cooperative research centre funding etc)
- Business support schemes (incentives/financing, advisory/support)
- Public procurement targets/guidelines for assets
- Provisions of public infrastructure to support the ecosystem
- Regulatory frameworks (targets, product regulations, waste regulations, other regulations, reporting regulations)
- Fiscal frameworks (tax changes/support).

Each of these interventions has the potential to increase confidence and reduce risk for all CBMs – from design to use and recovery.

In 2019, the European Commission approved €3.2 billion in national incentives for research and innovation projects across the battery value chain.[113]

113 European Commission: *Commission approves €3.2 billion public support by seven Member States for a pan-European research and innovation project in all segments of the battery value chain*

The influence of some players is greater than others. China, the EU and the US are significant producers and consumers of LIBs, and their role will be more significant than others.

Working together

Government has an important role to play in leading partnerships between the public and private sector, as well as creating the environment and schemes within which partnerships and innovation can occur. These partnerships will have to bring together players from across the supply chain and across industries. For example, to enable certain sharing models, the automotive industry and grid operators will have to coordinate activities.

Governments will also have to harmonise approaches across borders, given the global nature of the LIB supply chain. The EU is leading as policy makers in many ways. In 2018, the European Commission signed an agreement on innovation with European manufacturers aimed at facilitating the reuse and recycling of EV LIBs.

Toolkit for Policymakers
Ellen MacArthur Foundation

This toolkit provides insights, a step-by-step approach and eleven tools for creating policies that promote circular behaviour, alongside a case study in Denmark.

Policy intervention types, methods for identification and prioritisation of ideas, and qualitative and quantitative tools for estimating value, implications and barriers, are just some of the contents of the report designed to enable policymakers to take the first steps towards creating circular industries.

China is expected to capture 41% of the revenues from the global battery supply chain in 2030. This is in line with their anticipated demand for EVs – 43% of the market in 2030.[114]

114 World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

Industry

Industry should demonstrate leadership and collaboration through partnerships, data sharing initiatives and designing for reuse and disassembly.

Recommendations

Address gaps in data and information – both new businesses and existing ones

Design batteries for cascading reuse and ease of disassembly

Lead public-private partnerships to develop scalable projects that address local and global environmental concerns

Data

Data is a key enabler for the circular economy. The right data systems and product/material tracking systems could easily inform recyclers what a battery is made of, provide access to instructions for disassembly or repair, and enable the use case and performance of batteries to be tracked over their first, second or later uses, providing visibility over who is responsible for them at their EOL.

In Australia, the CSIRO has identified that the "variability and difficulty in collecting data illustrates the difficulties in understanding stocks and flows for LIBs from sales to EOL, and poses challenges for forecasting and predicting future trends".[115] Given the low levels of collection and recovery in Australia, improvements in tracking will play an important role moving forward.

Design for reuse and disassembly

Increasing modularisation, reducing the number of steps and tools required for disassembly and sharing information on materials and disassembly are just some steps that could be taken. Most of the consideration of design for reuse and disassembly is concentrated in academic research, and yet designing for reuse and disassembly are key enablers for many CBMs. Therefore, creating a feedback loop between academia and the LIB industry could help to unlock several CBMs.

Lead public-private and private-private partnerships

Industry can integrate and demonstrate the use of new technologies like intelligent labelling, blockchain, Internet of Things to improve lifecycle management, battery health management, and reuse and recycling.

As an example, Everledger is an emerging blockchain-based business that has partnered with Ford and received funding from the US Department of Energy. Everledger will be completing two pilots.

"The first pilot is a collaboration with Ford Motor Company, connecting stakeholders in its EV battery lifecycle to ensure optimal management and responsible recovery at end-of-life. The second pilot focuses on a platform to inform and reward consumers for recycling portable lithium-ion batteries and the portable electronics they power."[116]

Importantly, Everledger is collaborating at a global scale too, through support of the Global Battery Alliance and national-level organisations such as the New Zealand Battery Industry Group.

MaaS and other shared mobility business models will be key to increasing the utilisation of LIBs in EVs. Private industry has the opportunity to lead governments in this area by working with them to implement solutions across private and public transport systems, and assisting the development of supportive legislation.

115 King S, Boxall NJ, Bhatt AI (2018) *Lithium battery recycling in Australia, CSIRO, Australia*

116 Everledger: Batteries life cycle management

"Our investment conviction is that sustainability – and climate – integrated portfolios can provide better risk-adjusted returns to investors. And with the impact of sustainability on investment returns increasing, we believe that sustainable investing is the strongest foundation for client portfolios going forward."[117]

Blackrock, the world's largest asset manager with US$7 trillion under management, noted this in an open letter to clients in 2020.

117 Sustainability as BlackRock's New Standard for Investing

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Investors

Investors with social and environmental impact objectives should work with government and industry to coordinate and prioritise investment into the most effective CBMs.

Recommendations

Leverage impact investment to achieve beneficial social and environmental impact alongside a financial return

Coordinate and prioritise investment into the most effective CBM opportunities

Consider the resilience impact and benefits of CBM opportunities

Work with industry and policymakers to develop the conditions that promote and grow CBM investments

Impact investment

Currently, and in the absence of government intervention, CBMs can have lower returns than the traditional linear business models. Therefore, in order to realise the benefits that CBMs provide, investors need to consider their investments over a wider range of metrics than financial return, and/or over a longer time horizon.

The growing trend towards impact investment shows an increasing willingness to accept lower financial returns against higher environmental and social returns. These longer-term sustainable investments could make up part of an impact investment portfolio or be bundled and sold in the market as green investment products, such as green bonds.

Coordinated investment

In order for investment to be most effective, investors should work collaboratively with industry and other investors to invest in the most effective CBMs. Investors can help fund emerging companies develop novel technologies or innovative services to advance aspects of the circular economy.

In Australia, most recyclers are currently operating at a small scale. Investment is required to enable these companies to scale-up their technology, logistics and processes. Careful consideration should be given to fund recycling technology that can continue to provide the greatest long-term impact to the ecosystem.

Research will continue to play an important role in the transition to a circular economy. Venture capital can help fund innovative research and support early-stage companies commercialise new technologies.

One area of research is solid-state LIBs. These have a solid cathode and offer greater energy density, as well as a higher operating temperature (and therefore less cooling capacity is required). Research is currently underway to develop a scalable solid-state LIBs.

Resilience impacts

CBMs also provide the opportunity for investors to future-proof investments. By investing in CBMs, investors can reduce their reliance on primary resource extraction and linear supply chains. This will increase the resilience of their assets in a resource constrained future.

Investors should consider their resilience exposure when analysing new investments and consider how and when a lack of resilience may become problematic. This practice of resilience risk assessment should lead to prioritisation of projects with circular elements over time as primary resources become scarcer.

Collaboration

Investors can work with industry and government to develop the environment in which CBMs grow. They can work together to develop the regulations and policy that promote and grow investment in CBMs.

Together

Together, the whole industry will need to increase collaboration and coordination in order to loop back material flows and increase the value kept in the supply chain.

Recommendations

Establish, grow and fast-track partnerships across and outside of the supply chain, and grow global initiatives

Decarbonise production processes and national grids

Standardise battery design and data management processes, including labelling and materials passports

Partnerships and global initiatives

CBMs rely heavily on collaboration within and outside of the supply chain. Designers and manufacturers need to understand the requirements of recyclers, who need access to reliable recovery providers to provide supplies of used batteries.

Second-life applications also require assurance over the supply and quality of used batteries. And everyone should have visibility over the social and environmental lifecycle impacts of their products and materials.

Partnerships, R&D, and pilot programs will enable trust and economies of scale to be achieved. Examples of collaboration across the supply chain and governments continue to emerge. These should be used as an ongoing evidence base, and include:

- Renault Group signed up to the French Government's *Circular Economy Roadma*p, focusing on moving towards 100% plastic recycling in France by 2025[118] and has partnered with Veolia on the recovery and recycling of LIBs
- RecycLiCo is a patented hydrometallurgical process from American Manganese Inc, which is also collaborating along the value chain by partnering with Kemetco Research Inc on a demonstration plant and working with Battery Safety Solutions, which supports the process through logistics and disassembly
- The ReCell Center, created by the US Department of energy, has brought together researchers and industry looking to create a closed-loop battery industry. The US is looking at a market-led approach, with extended producer responsibility not central to their strategy at a federal level.

Given the global nature of the supply chain and the challenges faced, global alignment is a must.

LIBs will have an essential role to play in meeting the Paris Agreement target. The WEF's vision for 2030 is that they will enable 30% of the required emissions reductions in the transport and power sectors.[119] However, for the benefits of LIBs to be maximised and for the world to fully address the challenges of climate change and unsustainable development, global coordination in how the industry develops will be essential.

"The Global Battery Alliance is a public-private collaboration platform of 70 public and private sector organisations founded in 2017 that has become the global platform to help establish and collaborate on a sustainable battery value chain".[119]

118 Interview – Renault Group

119 World Economic Forum, Global Battery Alliance, 2019, A Vision for a Sustainable Battery Value Chain in 2030

Decarbonise

Reducing carbon emissions is needed across the LIB value chain. In production, an increase in the renewable energy used in factories would have a significant effect on embodied carbon. The energy mix used in national grids is also incredibly important – EVs need to be charged by green energy to facilitate the kind of global decarbonisation of the transport sector that's needed to meet emissions reduction targets.

Standardise

The more LIBs can be standardised and accompanied by product labelling, the more easily processes can be developed to share, test, reuse and disassemble them.

Design standards should include principles and processes for standard disassembly and data management – highlighting availability of information on material composition, recycling methods and disassembly steps.

Standardisation of chemistries will enable the waste industry to plan for future waste streams. Of course, this should be balanced with requirements for innovation and it is important that industry-wide discussions establish the most appropriate ways forward.

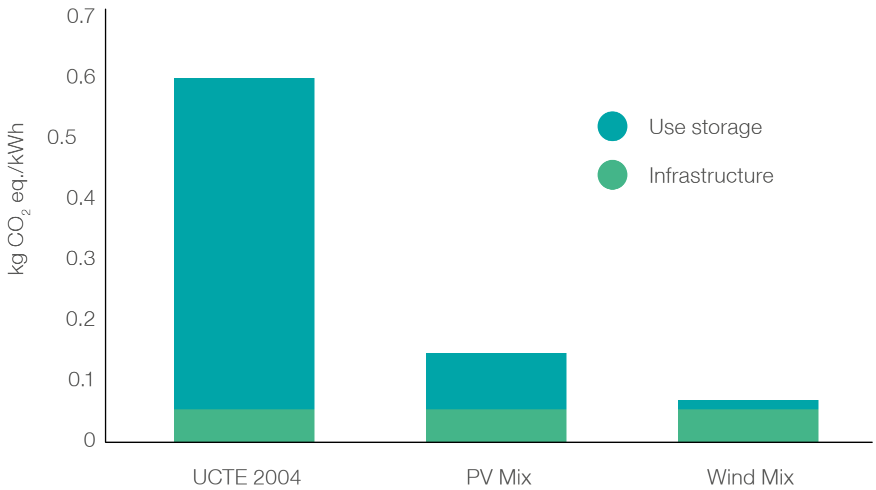


Figure 14: Overall climate change impacts of a Li-ion battery while using different energy mixes.[120]

120 Notes: LMO battery 1 kWh in EU. Union for the Co-ordination of Transmission of Electricity 2004 – mostly coal and natural gas – indicative of typical EU a decade ago.

Oliveira, L.; Messagie, M.; Rangaraju, S.; Sanfelix, J.; Hernandez Rivas, M.; Van Mierlo, J.;2014, *Key issues of lithium-ion batteries e from resource depletion to environmental performance indicators*

Conclusion

If the world is to develop sustainably, run efficiently and find new sources of value, we need to reduce the waste produced by all sectors.

The circular economy presents an opportunity to address these adverse outcomes and shift to a more sustainable and resilient supply chain. It is expected that CBMs will represent a US$4.5 trillion global growth opportunity that contributes to sustainable economic development.

Renewable energy underpins the circular economy and LIBs will play an important role in the required shift to a more renewable, resourceful and low-carbon future. However, the ways in which LIBs are currently made, used and disposed of are incompatible with this sustainable future. The current linear lifecycle of most batteries leads to adverse environmental, social and economic outcomes globally.

Through research, interviews and application of circular business models, this report demonstrates the significant opportunities for value capture that are present and ready to be explored by industry participants globally.

This report aims to harness the opportunities and stimulate circular economy leadership in the LIB industry.

With the industry on the cusp of exponential growth in the uptake of LIBs globally, policymakers, industry and investors need to work together to establish the policy, technology and business models that enable a circular economy for the industry.

To recap, the seven CBMs that could be applied to the LIB industry are:

Product and process design: rethinking design to improve the maintenance, repair, upgrade, refurbishment and/or manufacturing process.

Circular supplies: replacing virgin materials with those sourced from within the circular economy.

Sharing platforms: enabling or offering shared use, access or ownership so more people can benefit from the asset.

PaaS: delivering performance rather than products, where ownership is retained by the service provider.

Lifetime extension: extending the service life of products through engineering solutions or via new applications.

Refurbish and maintain: repairing and refurbishing part or whole of the asset so it can be returned to operations or sold at the typical EOL.

Recycling: transforming waste into raw materials and retuning it to the circular supply chain.

Recommended steps

Policymakers should foster a supportive regulatory, research and business environment for CBMs locally and internationally.

- Implement product stewardship schemes to allocate responsibility for LIB components and materials
- Develop financial incentives and use policy levers to spur demand for circular solutions
- Work with industry and across governments to facilitate standardisation where appropriate

Industry should demonstrate leadership and collaboration through partnerships, data sharing initiatives and designing for reuse and disassembly.

- Address gaps in data and information for both new and existing businesses
- Design batteries for cascading reuse and ease of disassembly
- Lead partnerships to develop scalable projects that address local and global environmental concerns

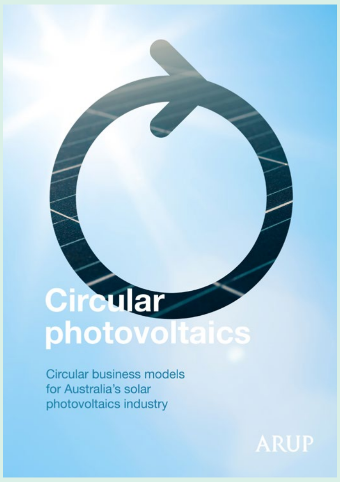
Investors with social and environmental impact objectives should work with government and industry to coordinate and prioritise investment into the most effective CBMs.

- Leverage impact investment to achieve beneficial social and environmental impact alongside financial return
- Consider the resilience impact and benefits of CBM opportunities
- Coordination and prioritisation of investment into the most effective CBM opportunities
- Work with industry and policymakers to develop conditions that promote CBM investment

Together, the LIB industry will need to increase collaboration and coordination in order to loop material flows and increase the value kept in the supply chain.

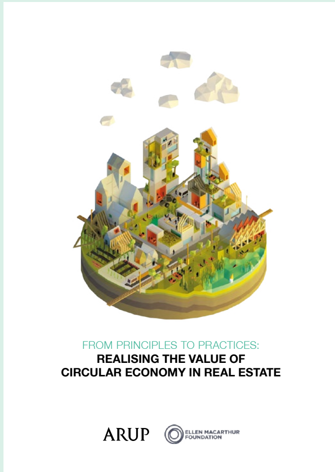
- Establish, grow and fast-track partnerships across and outside of the supply chain, and grow global initiatives
- Decarbonise production processes and national grids
- Standardise battery design and data management processes, including labelling and materials passports

Further reading



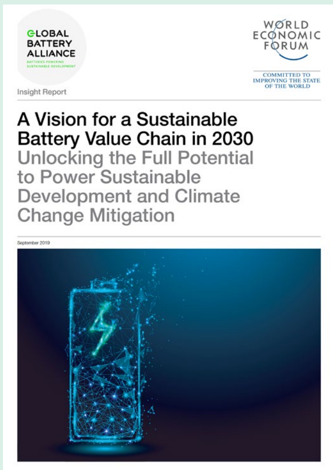
Circular photovoltaics
Arup

First steps towards a circular built environment
Arup



Realising the value of circular economy in real estate
Arup

Toolkit for Policymakers
Ellen MacArthur Foundation



A Vision for a Sustainable Battery Value Chain in 2030
World Economic Forum

Universal circular economy policy goals
Ellen MacArthur Foundation

Glossary

CBM	Circular business model
EOL	End-of-Life
EMF	Ellen MacArthur Foundation
EPR	Extended Producer Responsibility
ESS	Energy Storage Systems
EU	European Union
EVs	Electric vehicles
IEA	International Energy Agency
LABs	Lead acid batteries
LIBs	Lithium-ion batteries
MaaS	Mobility-as-a-service
PaaS	Product-as-a-service
R&D	Research and development
SoH	State-of-health
V1G/V2G	Vehicle-to-grid
WEEE	Waste Electrical and Electronic Equipment
WEF	World Economic Forum

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