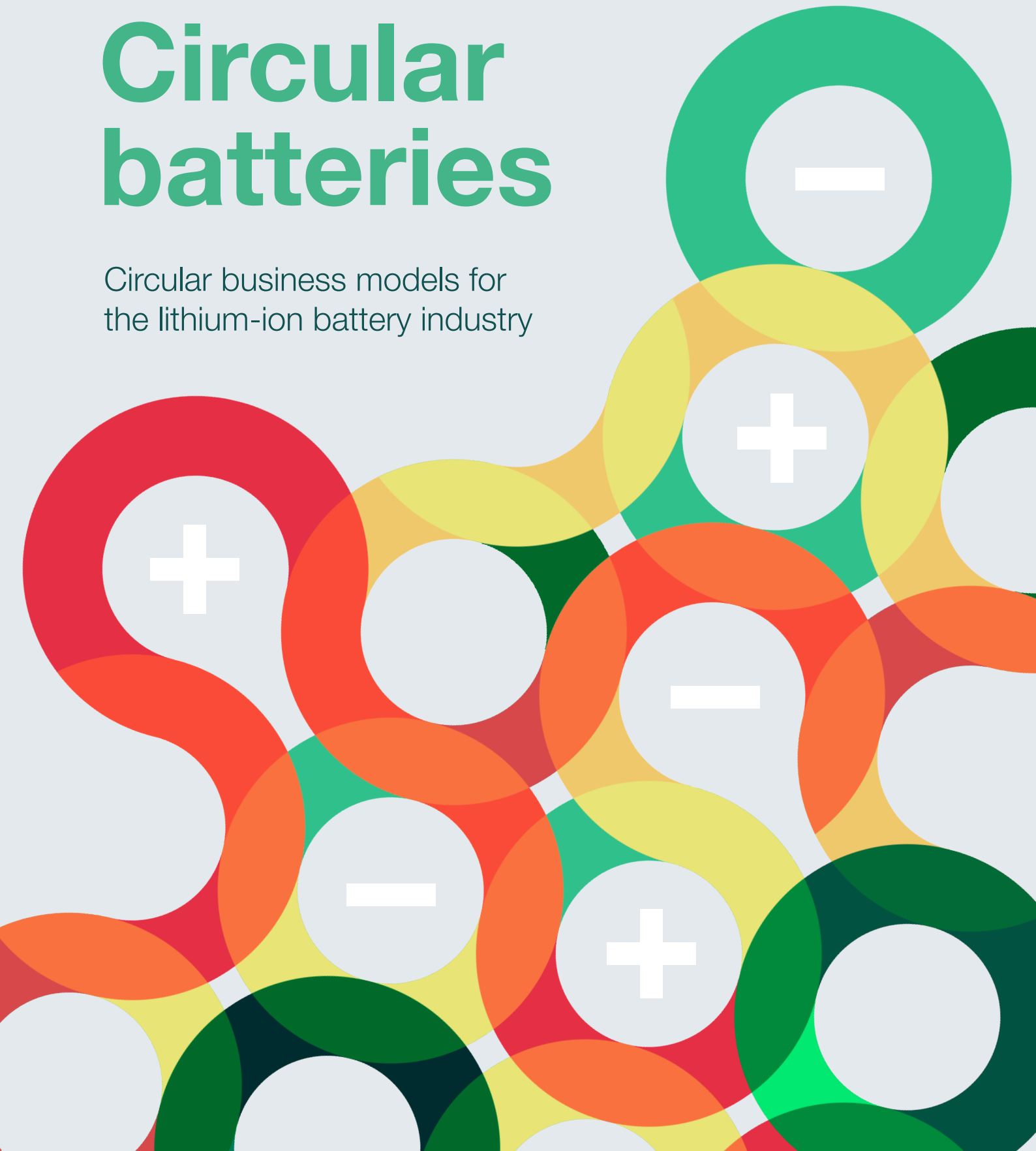


# Circular batteries

Circular business models for  
the lithium-ion battery industry



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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.

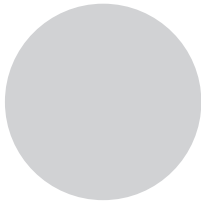


### **Responsible Consumption and Production**

Achieving this contributes to the United Nation's 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 this Goal as well and combined with the circular economy concept could generate significant economic, environmental and social value. It influences Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation and Infrastructure) and, of course, Goal 17 (Partnerships for the Goals).





## Preface intro

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Name  
Title

Signature

## 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 not compatible 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 \$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 context of the LIB industry opportunity by:

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

**\$4.5tn**

CMB global growth opportunity

Through research, interviews and application of circular 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, policy makers, 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

Implement product stewardship schemes to allocate responsibility for LIBs

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

Work with industry and other governments to facilitate standardisation where appropriate



### Business

Address gaps in information databases to support materials tracking, classify standard modules, and improve testing and forecasting of battery life

Design batteries for cascading reuse and ease of disassembly

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



### Investors

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

Coordinate and prioritise investment into most effective CBM opportunities

Consider the resilience impact and benefits of CBM opportunities

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



### Together

Establish, develop 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



## Circular Business Model – statistics on opportunity value



### Product and process design

The World Economic Forum (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.



### Circular supplies

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



### Sharing platforms

Globally, if **50%** of EVs were enabled to be vehicle-to-grid compatible, **17 Mt** of carbon emissions would be saved per annum and **\$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 **\$70.4bn** by **2030**.



### Lifetime extension

The WEF estimated that if **61%** of EV batteries were re-used, **20 GWh** of ESS would be avoided, saving **1 Mt** of CO<sub>2</sub> and **\$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 **\$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 would 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 not compatible with this 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 and therefore 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<sup>1</sup>. LIBs have gained popularity among automobile manufacturers as they offer 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 now approaching a tipping point from which we expect to see the 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 per cent globally<sup>2</sup>.*

Traditionally used in consumer electronics during the 1990s and early 2000s, their applications are moving far beyond this small scale. In particular, they are being used increasingly in mobility applications: electric car 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<sup>3</sup>.

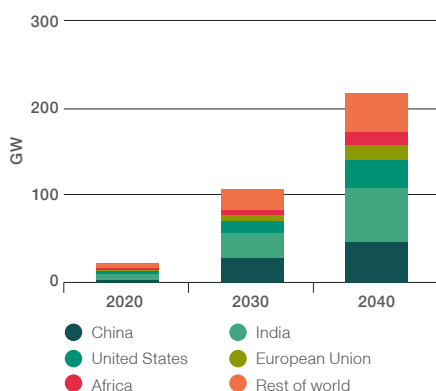


Figure 1: Installed capacity

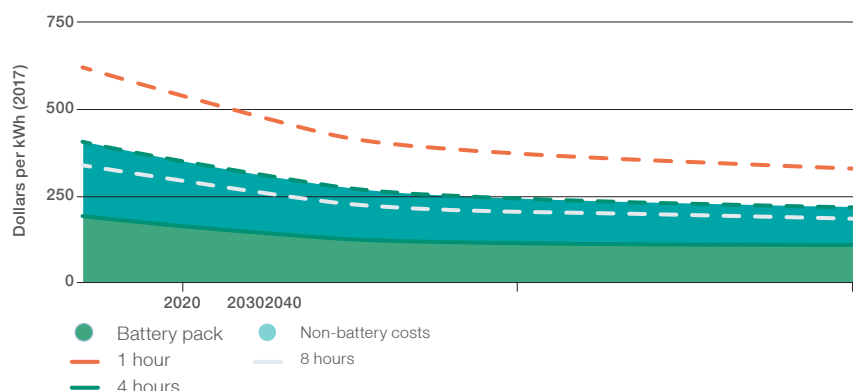


Figure 2: Capital cost

<sup>1</sup> \*Assuming global average carbon intensity of power generation

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

<sup>3</sup> International Energy Agency, 2019, *Global EV Outlook 2020*





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 ‘make, use and dispose’ model of the linear supply chain. This model has many fundamental problems, including supply chain security and inflexibility, 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, this represents not only environmental impacts, but also significant value of material that is being lost to landfill. They also create a potential ignition source in landfills, commonly leading to difficult-to-manage fires, causing increasing concern across the landfill management industry.

### The circular economy opportunity for LIBs

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 both existing players in the LIB industry to create more value, and for new services, jobs and programs to become new 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<sup>4</sup>.

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

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

The investors interviewed during research for Arup’s *First Steps Towards a Circular Built Environment*<sup>5</sup> 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 circular business models work. Arup’s previous report, *Circular Photovoltaics*<sup>6</sup> aimed to stimulate and encourage such leadership in the context of the solar PV industry in Australia. Circular Batteries aims to do the same for the LIB industry globally.

It does so by:

- Analysing the current state of the industry
- Outlining how circular business models 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.

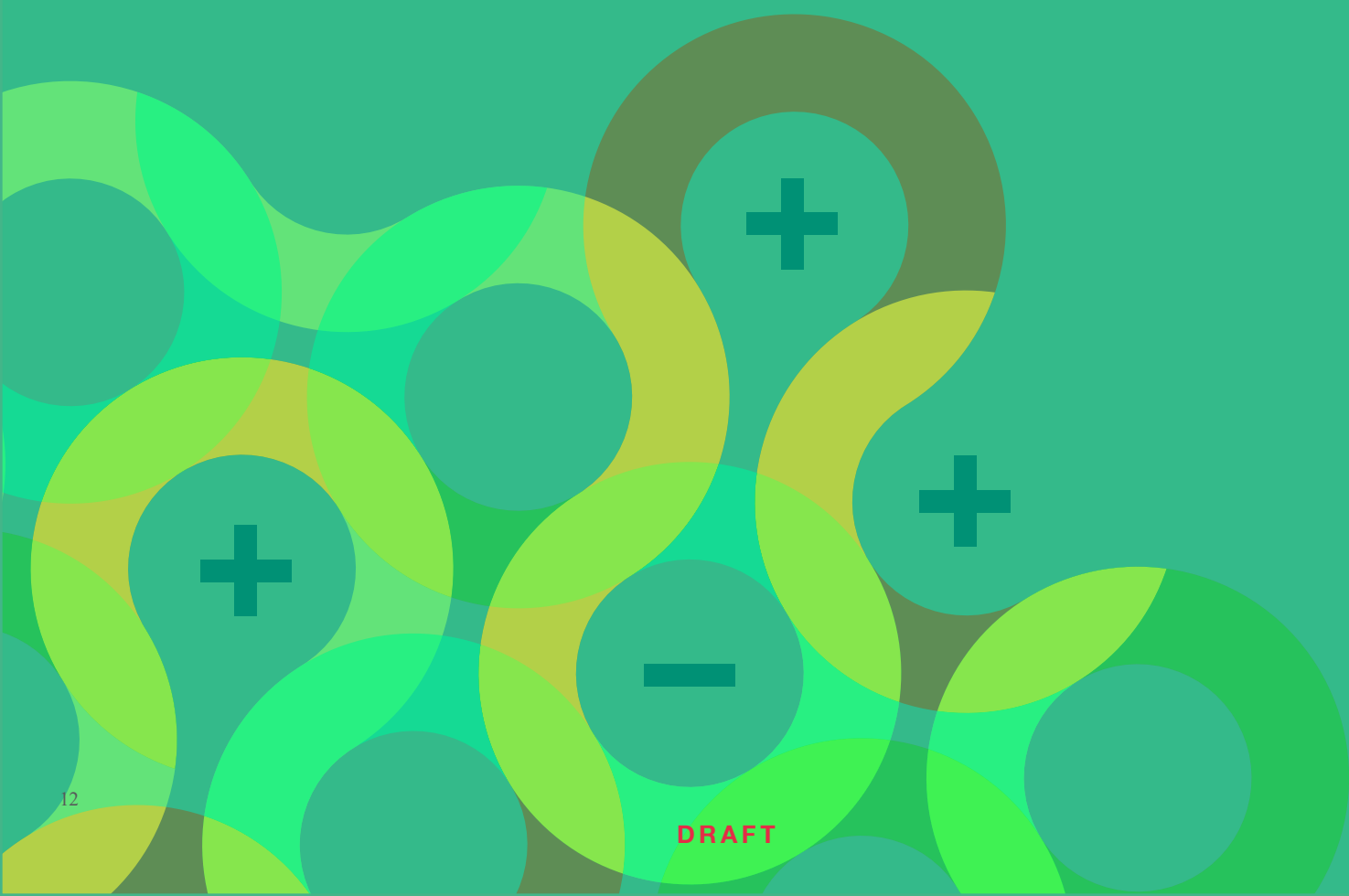
4 Ellen Macarthur Foundation, 2017, *What is the circular economy*

5 Arup, 2018, *First steps towards a circular built environment*

6 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, chemistry, performance, cost and safety characteristics vary across LIB types.

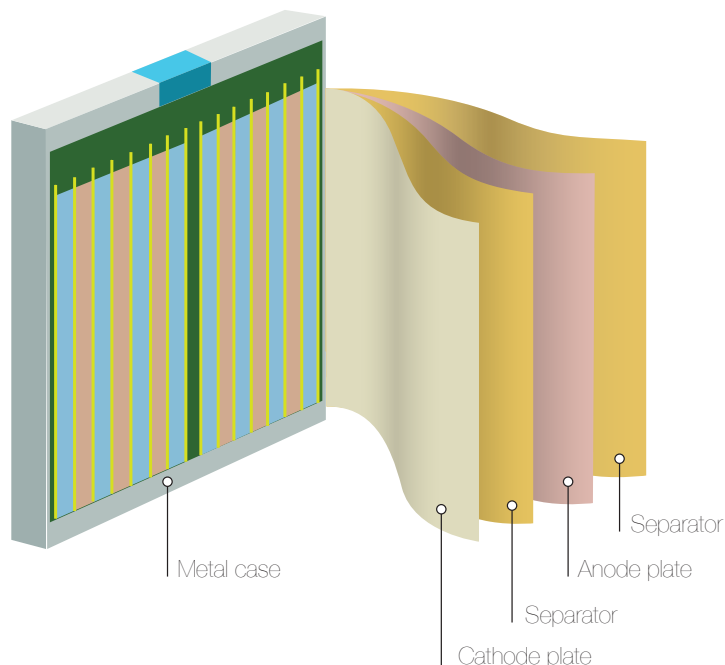


Figure 3: Prismatic Li-ion cell

### Common chemistries, their characteristics and uses

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

The forecast share of these chemistries to 2026 by Cairn ERA is shown in Figure 4.<sup>7</sup>

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

Considering specifically the global demand for LIBs from EVs, and the scarcity and relative cost of cobalt, NMCs with chemistries with higher nickel content and lower relative 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 preparation, there is a high degree of uncertainty around which LIB chemistries will be the dominant actor moving forward. This uncertainty is largely due to the levels of research and development occurring in the space.

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.

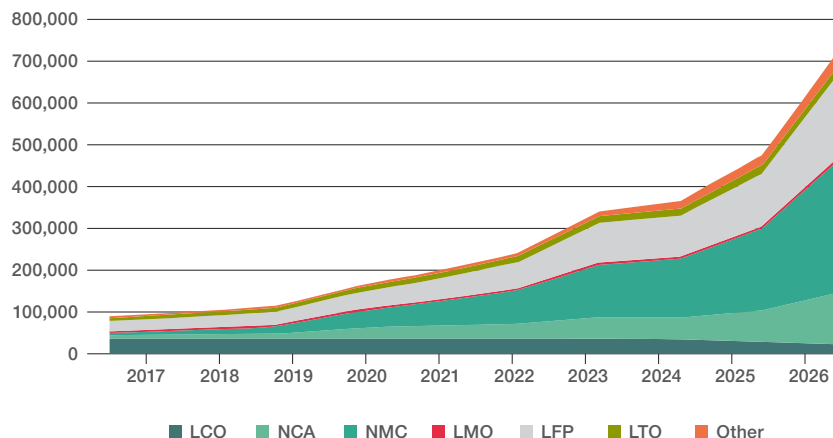


Figure 4: Global Battery Industry Growth Forecasts by Electrode Chemistry, in MWh, 2017-2026

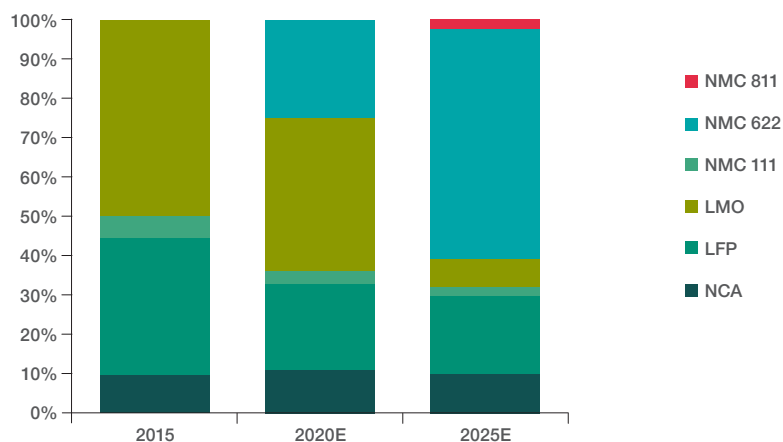


Figure 5: EV Battery Chemistry Market Share – BMO Capital Markets<sup>8</sup>.

<sup>7</sup> Cairn ERA via Jaffe, 2017, *Vulnerable Links in the Lithium-Ion Battery Supply Chain*

<sup>8</sup> 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<sup>9</sup>. 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 now emerging as the largest application category. Electric buses are becoming more common, and prototypes of electric ferries and even planes are also beginning to emerge<sup>12</sup>.

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

The numbers depend on policies enacted by governments between now and then<sup>13</sup>. While there is huge range in these numbers, the scale is 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 utility battery is the 100MW/129 MWh Tesla battery installation at Hornsdale Power Reserve in South Australia, which is being expanded to 150 MW/193.5 MWh.

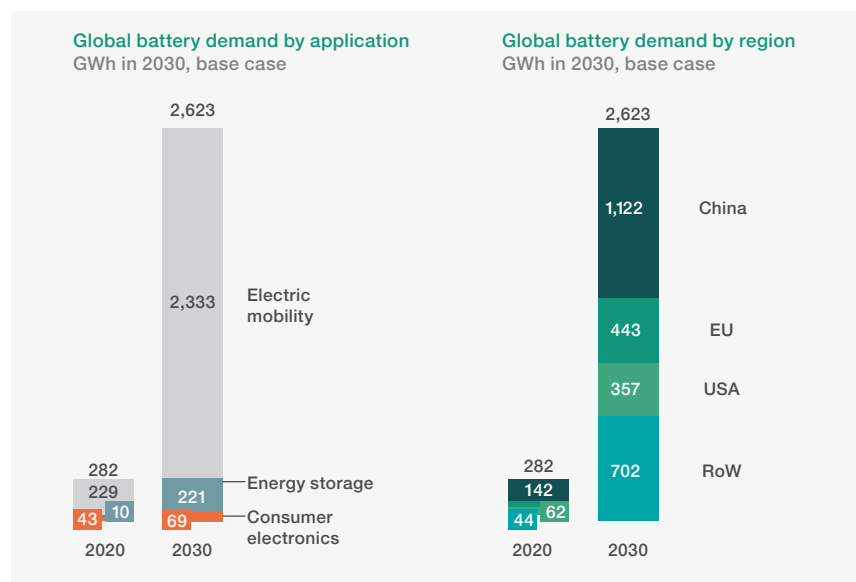


Figure 6: Global battery demand by application and region<sup>11</sup>.

This expanded battery will provide dispatchable power to support renewables in the region, ancillary services and virtual inertia to the grid<sup>14</sup>.

In 2018, the Asia Pacific region held the largest market share of any region<sup>15</sup>, and China is expected to dominate future demand. Car and electronics manufacturing operations bases are being shifted to China to provide better access to raw material supply and reduce labour and logistic costs.

The global lithium-ion battery market size is estimated to hit nearly

**US\$92.2bn**

by 2024<sup>10</sup>, as a result of the increasing demand from EVs.



<sup>9</sup> World Economic Forum, Global Battery Alliance; McKinsey analysis

<sup>10</sup> Markets and Markets, 2019, *Lithium Ion Battery Market by Type*

<sup>11</sup> World Economic Forum, Global Battery Alliance; McKinsey analysis

<sup>12</sup> [BBC News: Meet the electric pioneers](#)

<sup>13</sup> International Energy Agency, 2019, *Global EV Outlook 2019*

<sup>14</sup> [Hornsdale Power Reserve: Strengthening the South Australian Electricity Grid](#)

<sup>15</sup> [AP News Business Wire](#)

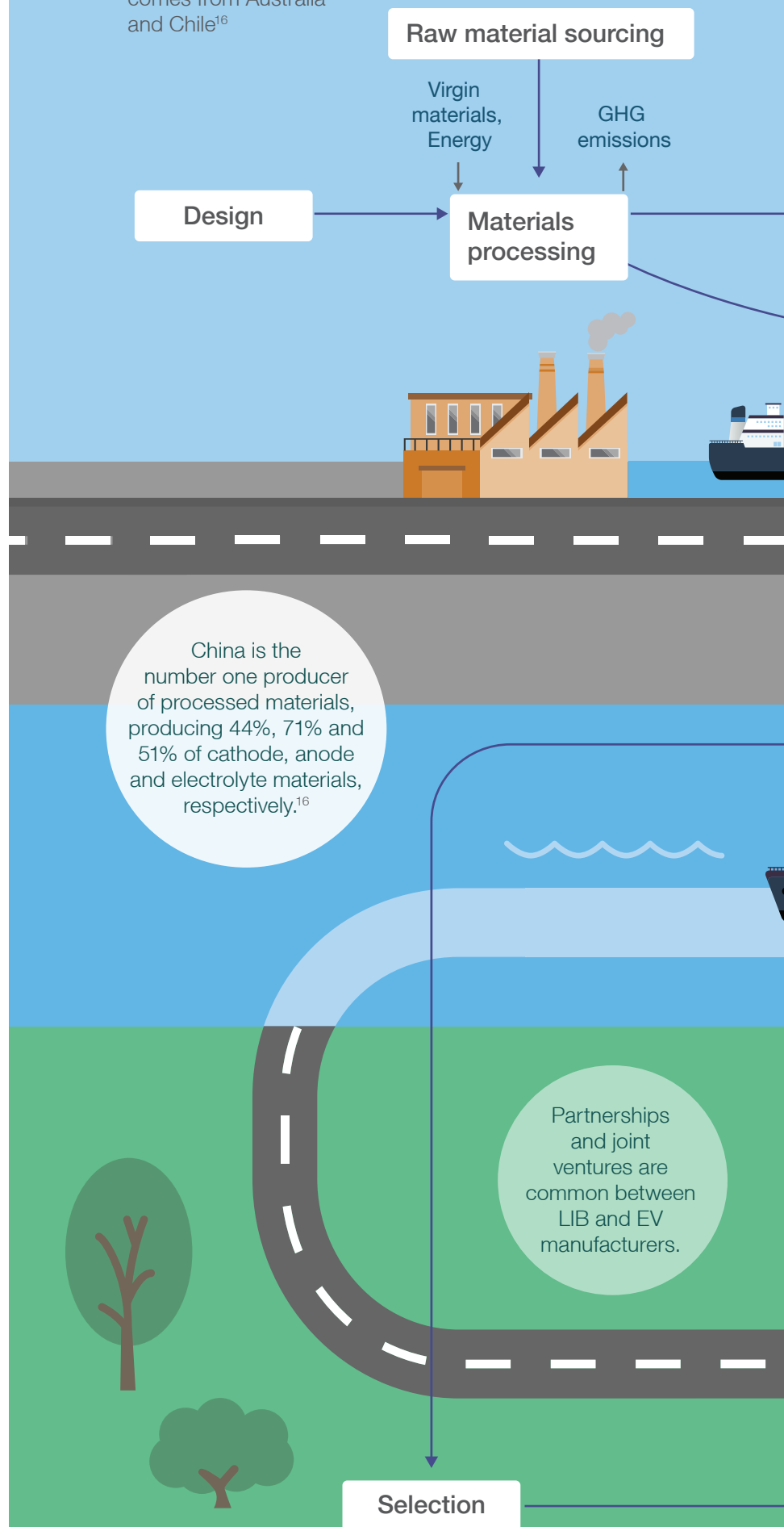
## A linear value chain

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.

75%

of lithium supply comes from Australia and Chile<sup>16</sup>



<sup>16</sup> European Commission, 2019, *Report on the Implementation of the Strategic Action Plan on Batteries*

<sup>17</sup> Future Smart Strategies, 2018, *A Lithium Industry in Australia*

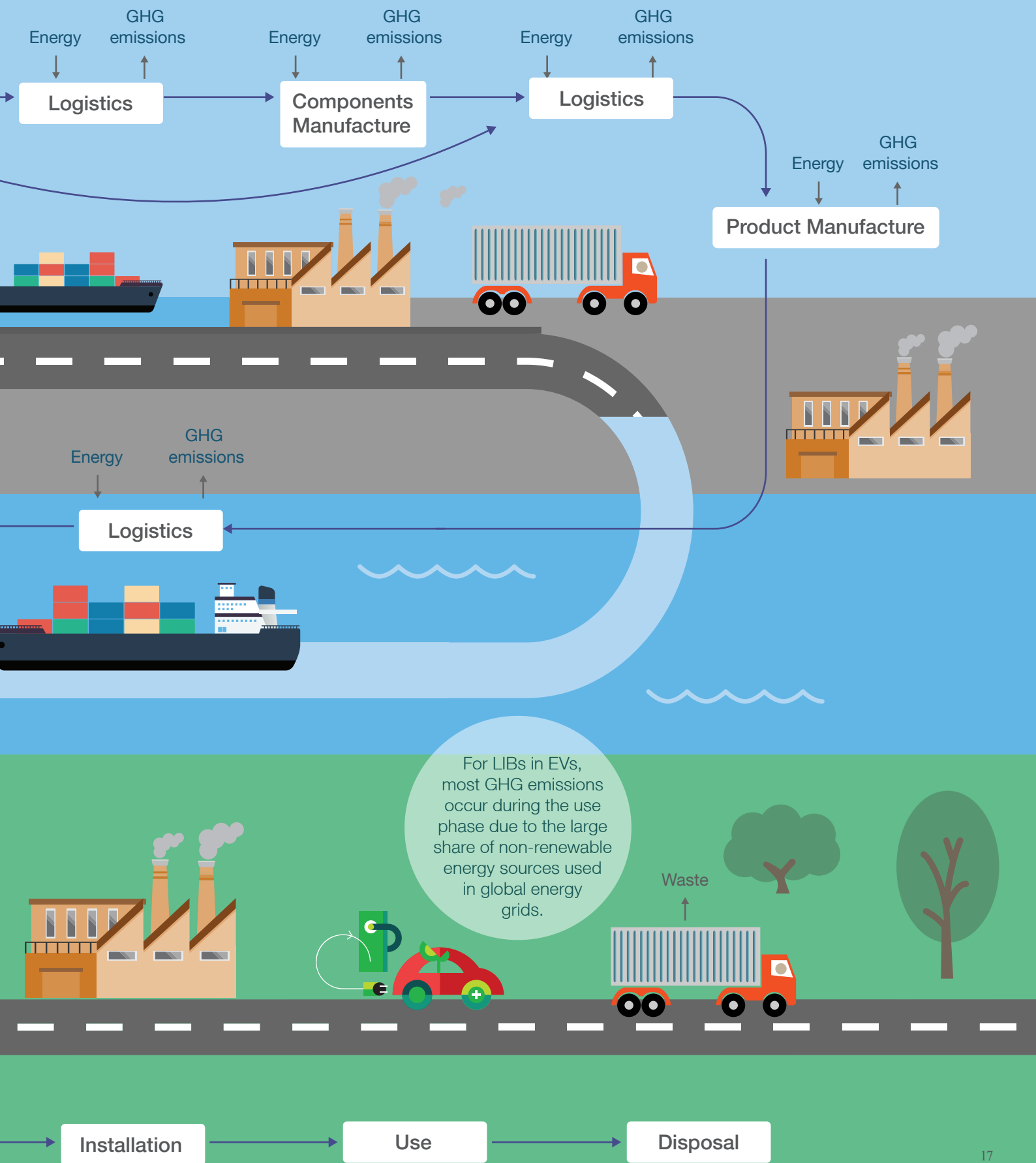
<sup>18</sup> International Energy Agency, 2020, *Global EV Outlook 2020*

US\$11.7bn  
Mining concentrate<sup>17</sup>  
LITHIUM VALUE CHAIN  
2025 FORECAST

50%  
of global EV battery  
manufacturing is in China<sup>18</sup>

US\$424bn  
Cell production<sup>17</sup>  
LITHIUM VALUE CHAIN  
2025 FORECAST

US\$1.3tn  
Module production<sup>17</sup>  
LITHIUM VALUE CHAIN  
2025 FORECAST



## Challenges

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**



**Lost value**



**Labour conditions  
and community impacts**

## Secure supplies

### There is plenty of lithium 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%)<sup>19</sup>.

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<sup>20</sup>, which is required for advanced LIBs with 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.

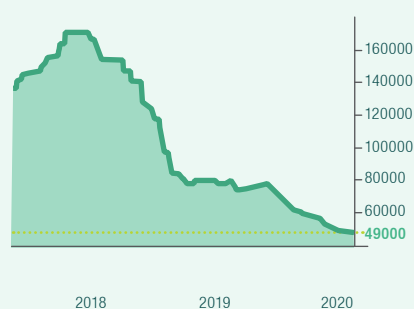


Figure 7: Lithium trading<sup>21</sup>.

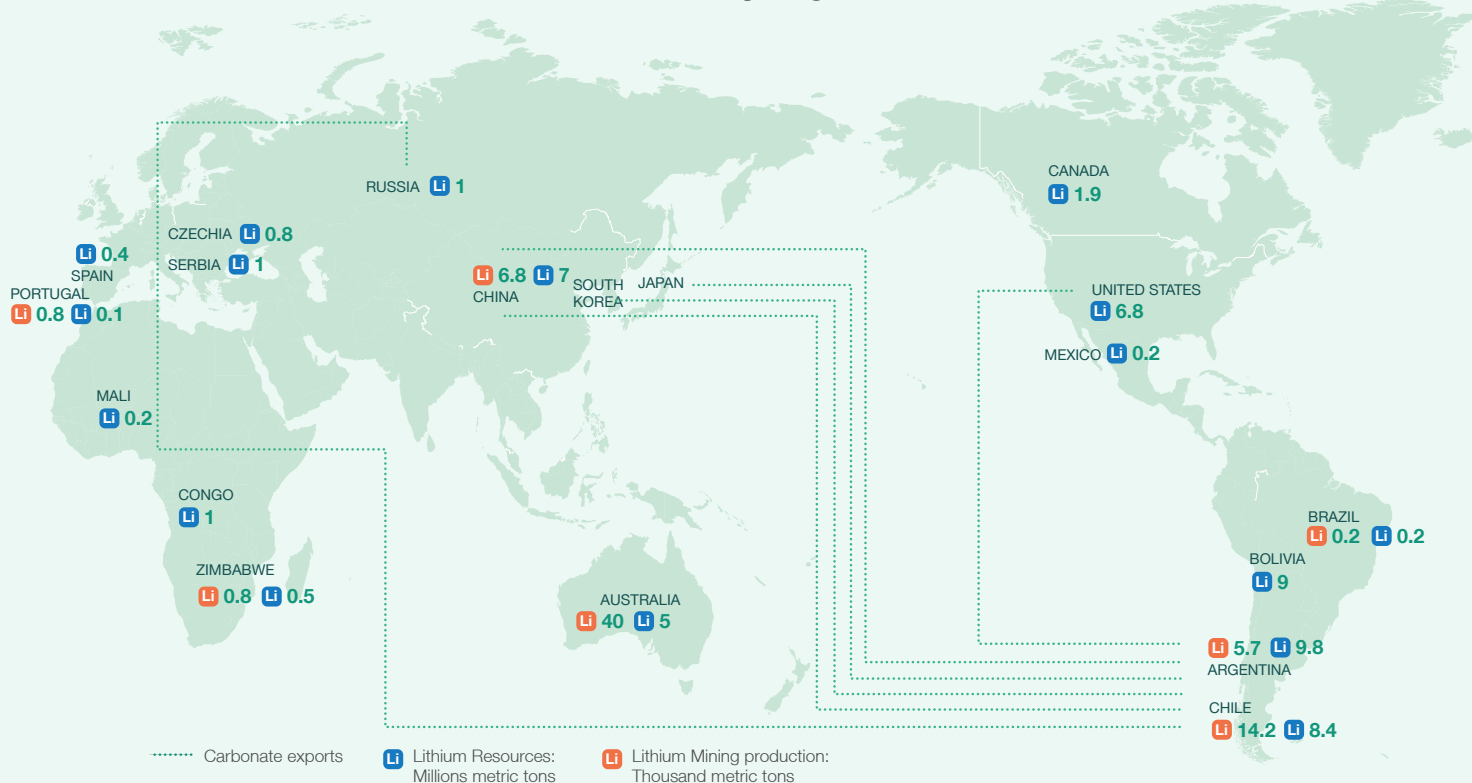


Figure 8: Lithium deposits<sup>22</sup>.

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*

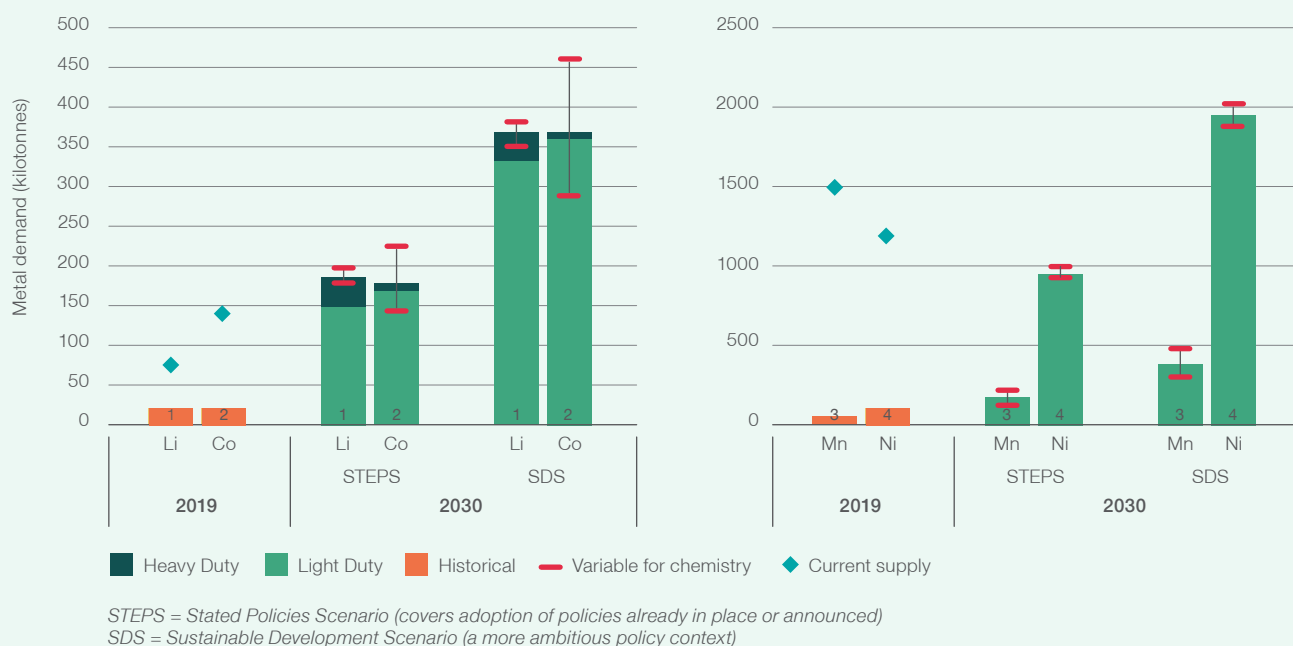


Figure 9: Annual demand for lithium [1], cobalt [2], manganese [3] and nickel class 1 [4] batteries from EV deployment, 2019-30<sup>24</sup>

### Global supply and demand of lithium is growing.

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 many new entrants to enter the market<sup>23</sup>. 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 would be 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 projected the demand for lithium in 2030 for each. The yellow bar was demand in 2019 with the blue dot 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 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<sup>25</sup>. 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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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<sup>26</sup>. Due to long battery lifetimes and multiple end uses, recycling is unlikely to provide significant short-term supply.

Cobalt is classed as a critical metal – it has a very high price reflecting this. Approximately 70% of cobalt production comes from one country – the Democratic Republic of Congo<sup>27</sup>.

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 used in many applications and it is anticipated that the demand for nickel in EVs will put pressure on the market and impact other applications such as stainless-steel production in the coming years<sup>27</sup>.

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

The IEA has also identified challenges beyond the sudden ramp-up of production. Environmental impacts – such as local pollution, CO<sub>2</sub> 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<sup>28</sup>.

<sup>26</sup> International Energy Agency, 2019, *Global EV Outlook 2019*

<sup>27</sup> World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

<sup>28</sup> International Energy Agency, 2019, *Global EV Outlook 2019*

## Embodied energy and carbon

Energy for the 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<sub>2</sub>-eq/kWh

The total embodied carbon emissions of LIBs<sup>29</sup>

This is the equivalent to driving a small internal combustion engine vehicle for 1,000km per kWh of battery storage<sup>30</sup>. The owner of a Tesla Model 3 Standard Range with a 50 kWh battery<sup>31</sup>, would need to drive for 50,000km using 100% renewable electricity to offset the embodied emissions of the battery alone, based on current emissions during production.

### Cathode material selection

Cathode materials generally require large quantities of energy to manufacture. Cathodes with nickel and cobalt have been found to be particularly harmful with the highest potential for environmental impacts, including global warming, resource depletion, ecological toxicity and human health impacts.<sup>32</sup>

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.<sup>33</sup>



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

30 *National Greenhouse Accounts Factor 2019*

31 *Electric Vehicle Data Base*

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

33 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.”<sup>34</sup>.

**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<sup>35</sup>. 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 caused water pollution in the Liqi river, causing damage to the local ecosystem including aquatic life.<sup>36</sup>



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

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

36 *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 be 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<sup>38</sup>, as have concerns over access to resources for indigenous populations or even simply the general population<sup>39</sup>. 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.<sup>40</sup>

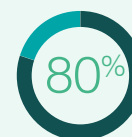
Social lifecycle assessments have highlighted the lack of data around these issues<sup>41</sup>. This is an area where more research is required, with a recent review of lithium mineral extraction identifying a limited focus on social and environmental impacts of the extraction<sup>42</sup>.

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<sup>43</sup>. Given the toxicity of metals like cobalt and nickel, high standards are required to minimize the cancer and non-cancer toxicity impact potential.<sup>44</sup>

Initiatives like the *Cobalt Industry Responsible Assessment Framework*<sup>45</sup> 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<sup>37</sup>

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

38 *National Geographic: Lithium is fueling- technology today at what cost*

39 *Business & Human Rights Resource Centre: The downside of electromobility*

40 *pv magazine: Is fair lithium from chile possible*

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

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

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

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

45 *Cobalt Institute: The cobalt industry responsible assessment framework*



## Lost value

The revenue opportunities of the LIB value chain are expected to be \$300 billion by 2030<sup>46</sup> and increasing beyond then. However, to create this opportunity, \$440 billion of investment is required before 2030.

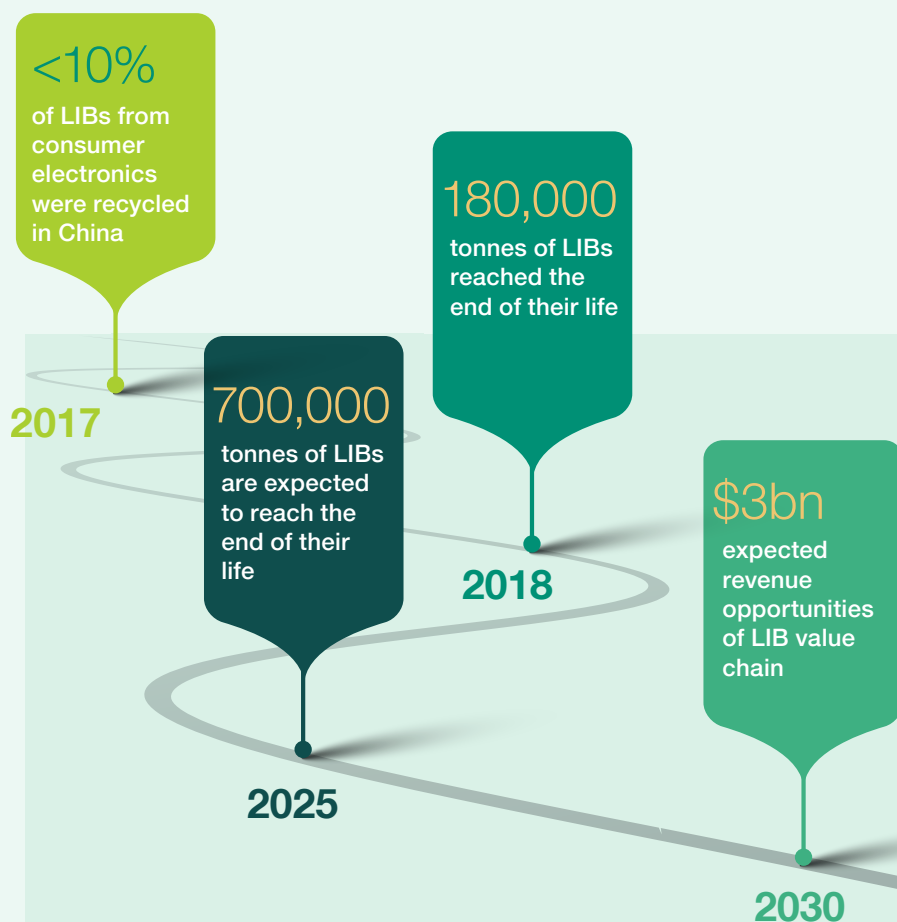
If this investment is not made, then there it is likely that much of this valuable material will be lost and the negative externalities realised by the global community. In China, it is estimated that less than 10% of LIBs from consumer electronics were recycled in 2017<sup>47</sup>. The rest went to landfill or remained idle.

In 2018, 180,000 tonnes of LIBs reached the end of their life. In 2025, this is expected to be over 700,000 tonnes<sup>48</sup>.

Around 50% of LIBs are recycled currently<sup>48</sup>. The other 50% are often stored, 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 end-of-life LIBs, driven by the high relative content and price of cobalt. These measures focus on LCO cathode chemistries which have a higher cobalt content. However, the supply stream for these lithium-ion batteries is still small, making it difficult to achieve economic returns from small scale operations.

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



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

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

48 [http://www3.weforum.org/docs/GBA\\_EOL\\_baseline\\_Circular\\_Energy\\_Storage.pdf](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 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

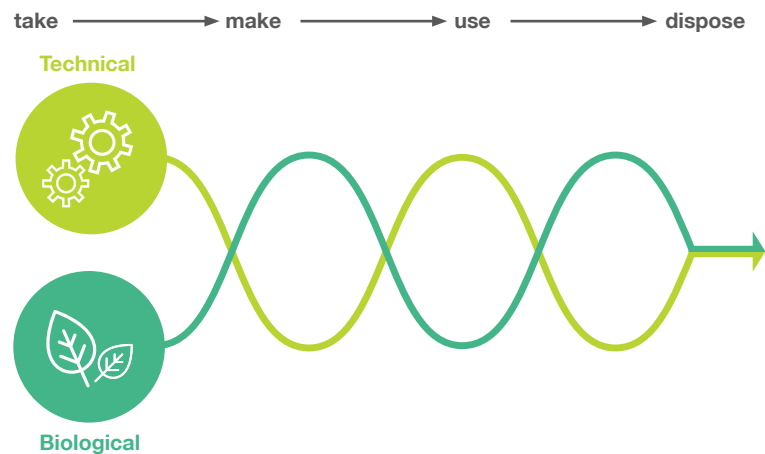
Looking beyond the current take-make-waste extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources and designing waste out of the system.

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 needing to work effectively at all scales – for large and small businesses, for organisations and individuals, globally and locally.

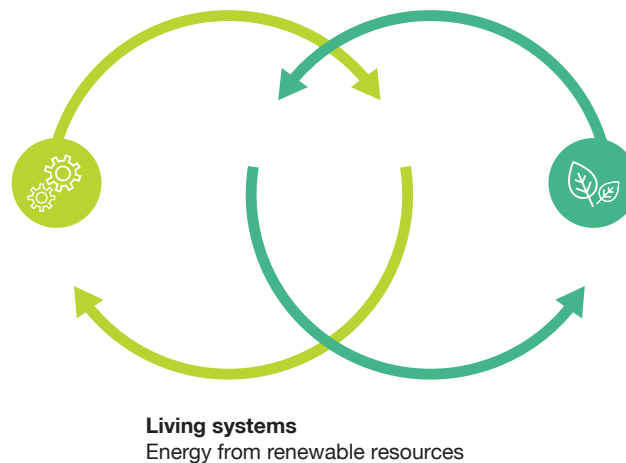
Transitioning to a circular economy does not just amount to adjustments aimed at reducing the negative impacts of the linear economy. Rather, it represents a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits. 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





### The economic potential for individual countries like Australia is significant.

For example, building on analysis from the CSIRO in Australia, a circular economy approach to LIBs could avoid 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 – a program from the EMF that facilitates collaboration, innovation and understanding between members looking to develop CBMs<sup>49</sup>.

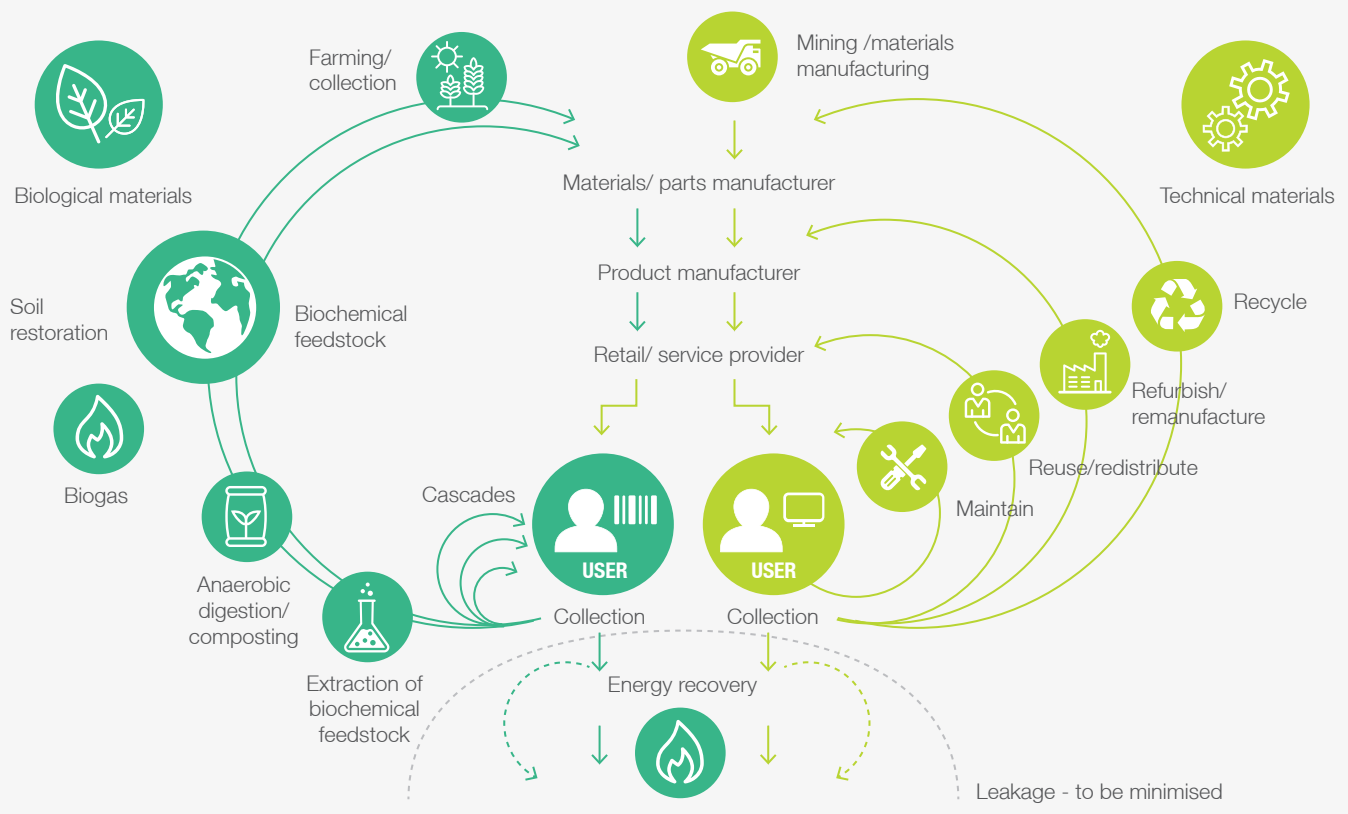
In 2018, China and the EU signed a Memorandum of Understanding on Circular Economy Cooperation<sup>50</sup>. The EMF estimates there is potential for CNY 70 trillion savings for businesses and households by 2040<sup>51</sup>.

49 Ellen MacArthur Foundation, 2018, Member Groups

50 [http://ec.europa.eu/environment/circular-economy/pdf/circular\\_economy\\_MoU\\_EN.pdf](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 consider the non-biological materials and aims to recover and restore products, components, and materials through strategies like reuse, repair, remanufacture or (in the last resort) recycling.



52 [www.circularity-gap.world/2020](http://www.circularity-gap.world/2020)

# Circular lithium lifecycle

23%

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

\$297bn

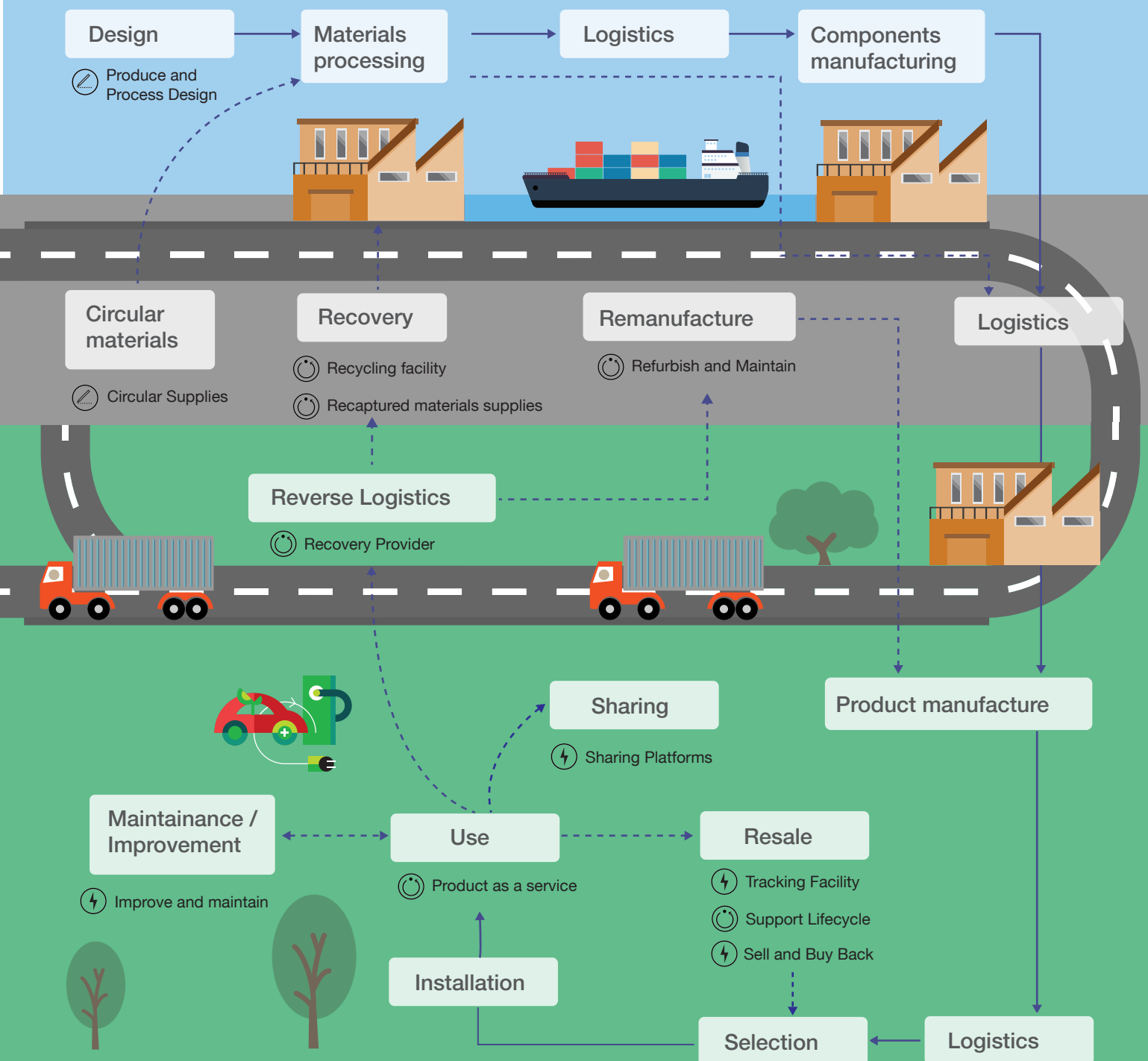
estimated market for electro-chemical production by 2025

\$22bn

additional value created if 50% of EVs were enabled to be vehicle-to-grid compatible

\$70.4bn

anticipated market for mobility as a service by 2030



\$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 represent spent batteries

DRAFT



## 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:



**Product and process design:** rethinking the 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.



**Product as a service:** delivering performance rather than products, where the ownership is retained by the service provider.



**Lifetime extension:** extending the service life of products, through engineering solutions or in 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 end-of-life.



**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 life cycle by enabling:

- Greater control of resource streams
- Innovation through the supply chain
- Enhanced collaboration within the supply chain
- Creation of services that capture value<sup>53</sup>.

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 about reducing total demand and increasing overall efficiency and impact too.



## 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 the design. This involves rethinking the 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.<sup>56</sup>

Designing a product that makes recycling or disassembly for refurbishment and reuse simpler, and/or creates the opportunity in the future for a new product that can be provided from the material resource contained in that 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 also not designed to be tested and characterised externally. Testing requires the development of a protocol that needs to be time and cost efficient. Politecnico di Milano is one research institution trying to address the lack of standardisation of battery modules<sup>54</sup>.

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 such as for 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 research and development (R&D) occurring, should be adopted. Government has a collaborative role to play in this.

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

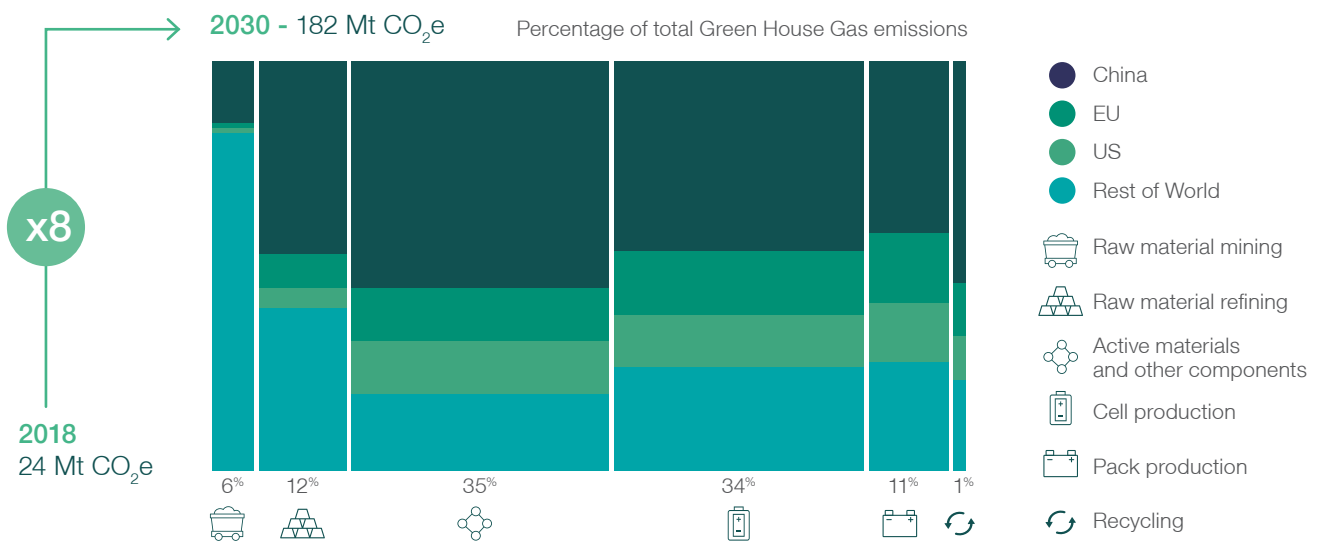
Designing for reuse may consider the modularity and replaceability of battery components that have shorter lifespans than other components. Designing for disassembly can also allow individual units, like controllers or cells, to be reused in other applications should the whole LIB unit reach its end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

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 require more 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<sup>55</sup>.

<sup>54</sup> [Interview – Politecnico].

<sup>55</sup> Wegener, Andrew, Raatz, Dröder, Herrman, 2014, *Disassembly of Electric Vehicle Batteries Using the Example of the Audi Q5 Hybrid System*

<sup>56</sup> Ellingsen, Majeau-Bettez, Singh, Srivastava, Valoen, Stromman, 2013, *Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack*



**Figure 10:** Battery production with significant CO<sub>2</sub> footprint, mainly driven by active materials and other components as well as production in China.

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 also 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<sup>57</sup>

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

Analysis from the WEF of the 2018 and 2030 carbon footprint of LIBs shows:

- The significant CO<sub>2</sub> 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. Additionally, this is only a base case and so there is opportunity to design out more carbon.

Important levers related to design to achieve this include:

- Improving process efficiency. This covers a broad range of improvements relevant to general manufacturing processes and also processes specific to LIBs such as using a solvent-less process in battery manufacturing to reduce energy requirements<sup>58</sup>
- 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, as shown below.

<sup>57</sup> Peiró, Ardente, Mathieux, 2017, *Design for Disassembly Criteria in EU Product Policies for a More Circular Economy*

<sup>58</sup> United States Environmental Protection Agency, 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion batteries for Electric Vehicles*

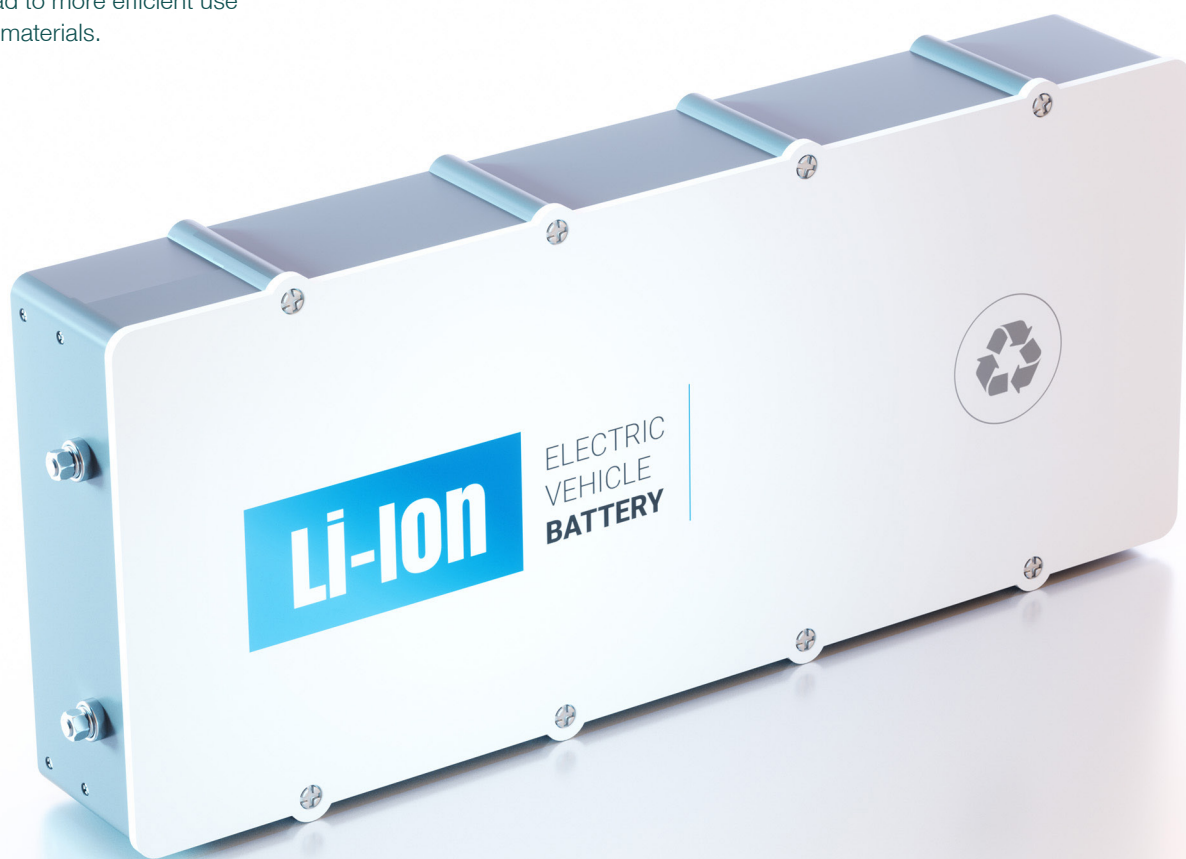
## Design opportunities include:

**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, then 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 end-of-life.

**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<sup>59</sup>.

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

<sup>59</sup> United States Environmental Protection Agency, 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion batteries for Electric Vehicles*

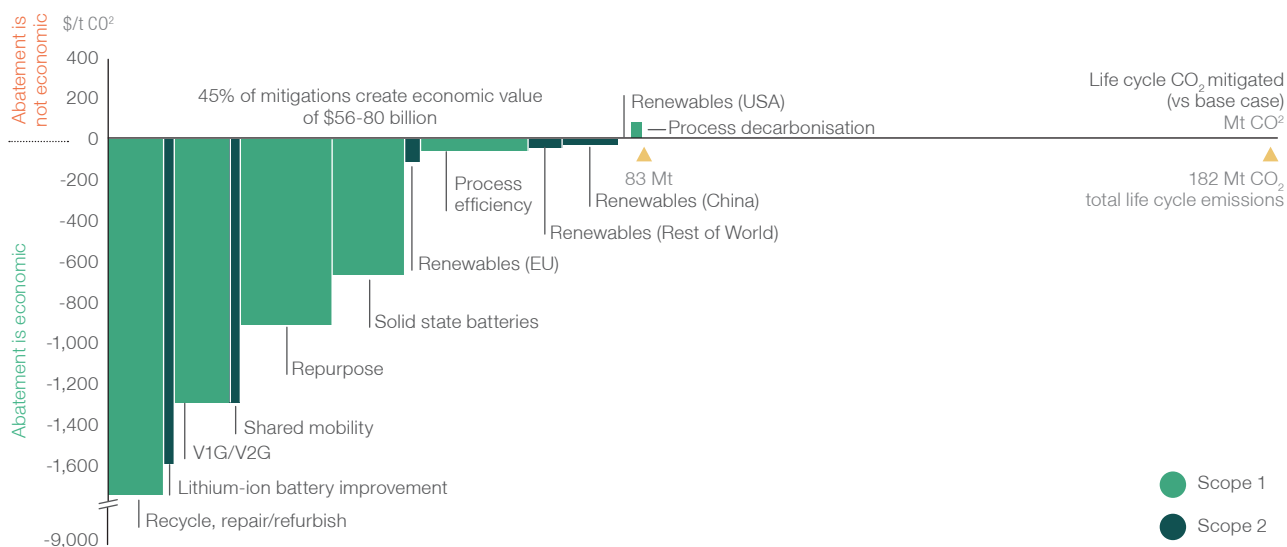


Figure 11: Relative costs of CO<sub>2</sub> mitigation (vs. base case).

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.

This means that they should lead efforts to collaborate around 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<sup>60</sup>.





## Benefits

Addressing the issue upfront makes all later stages of the life cycle easier

Reduction in material, finance, energy and emissions

Changes to design can be implemented immediately



## Barriers

Pace and competitiveness of research and development makes circular design a low priority

Lack of motivation from manufacturers given that 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 the end-of-life of the batteries. 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 and will be constantly evolving

**Labelling or materials passports** that track and disclose material origin and composition, recyclability and repair process. Global databases on LIB contents and recycling and repair instructions would accompany this

**Standardising** panel design by industry and government to enable more efficient recycling and to enable the waste industry to plan for future waste streams

The European Commission's new Circular Economy Action Plan<sup>61</sup> will play an important leadership role





## 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%<sup>62</sup>.

This will be 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 and 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, research and development, and pilot programs will enable trust and economies of scale to be achieved for the market for these materials.

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

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

Companies are emerging that capture lithium from existing applications, such as Lithium Australia, who have produced high-performance battery cells produced using lithium recovered from mine waste and spent lithium-ion batteries<sup>63</sup>. 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.**

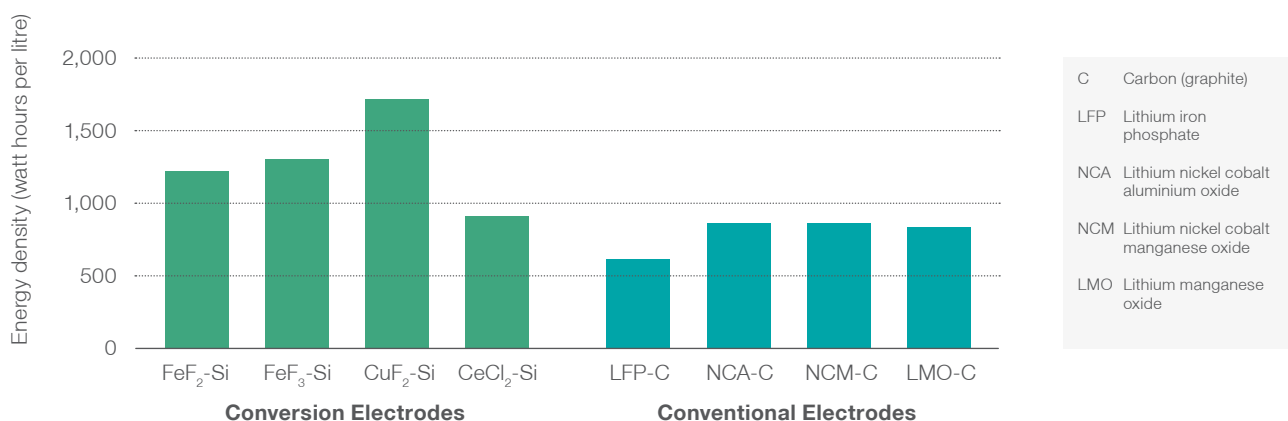
Product design should consider the security and ethics of supply chains. Following guidance, such as the Due Diligence Guidance for Responsible Mineral Supply Chains from the OECD, should be mandated.

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.

62 International Energy Agency, 2020, Global EV Outlook 2020

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



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

### 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 more desirable 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)<sup>64</sup>.

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



### Benefits

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



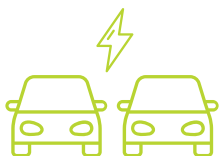
### Barriers

Lack of transparency  
Increasing level of demand for lithium, increasing pressure on production  
Uncertainty over future battery chemistries  
Low volume of end-of-life lithium to recycle  
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



### 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 the community members share a larger scale battery storage rather than smaller individual storage. 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 reduces emissions and costs for consumers and energy networks, and can reduce the need for additional storage.

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<sup>67</sup>, 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<sub>2</sub> savings due to reduced battery demand.

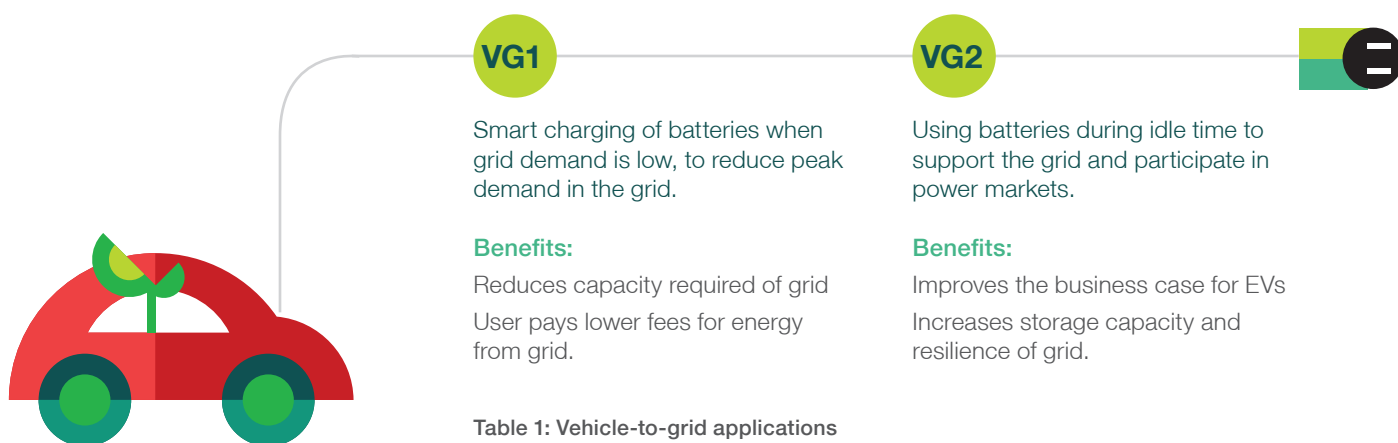


Table 1: Vehicle-to-grid applications

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 \$22 billion of additional value would be created<sup>65</sup>.

V1G/V2G solutions could lower costs for electric vehicle charging infrastructure by up to 90%.<sup>66</sup>

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

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

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

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 would be demanded overall.

While the transition to more sustainable forms of transport and energy storage is to be encouraged, this highlights the importance of the whole value chain transitioning to CBMs. This CBM relies on other parts of the value chain reducing waste and utilising circular materials. It also reflects the importance of ensuring 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 these projects up. 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



## 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 product as a service (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.<sup>68</sup>

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 end-of-life of the batteries.

Leasing is another way to provide a product as a service 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.



### 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

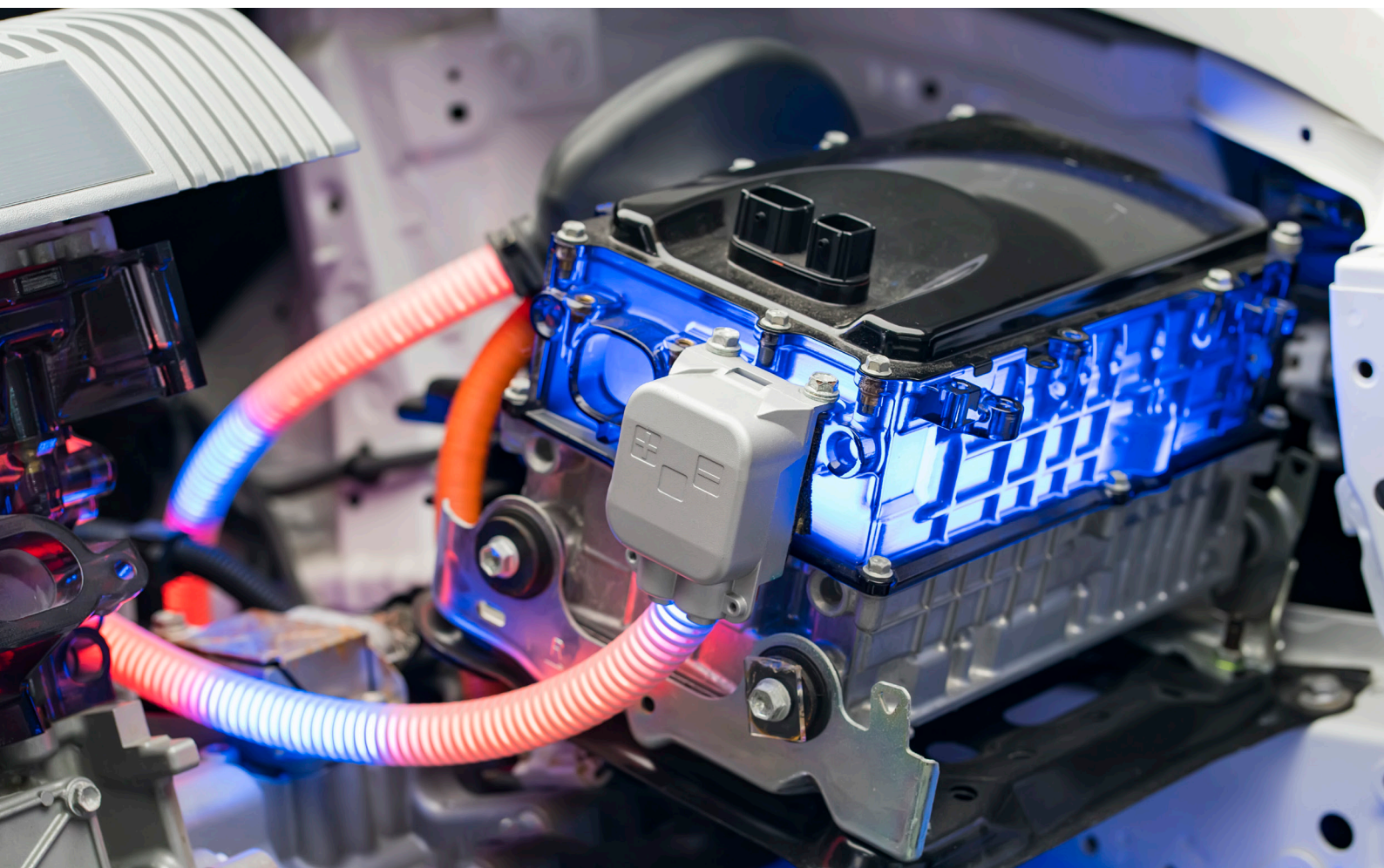
- Regulatory support** for EVs and autonomous vehicles
- Selection of EVs** by ride-share and taxi services
- Governments and private industry **developing and promoting PaaS models**
- Academia and incubators focusing on **creating innovative PaaS** business models



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.

Like with sharing platforms, these business models must overcome the emotional and status benefits of owning rather than renting.<sup>69</sup>

The mobility as a service market is anticipated to be worth \$70.4bn by 2030<sup>70</sup>.



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

70 *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.*

In EVs, LIBs are expected to last between 8 and 15 years.<sup>71</sup>

The WEF estimated that if 61% of EV batteries were re-used, 20 GWh of ESS would be avoided, saving 1 Mt of CO<sub>2</sub> and \$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%.<sup>75</sup>

The lifecycle assessments of LIBs demonstrate the significant emissions during the production phase<sup>72</sup>. 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 as previously discussed 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%<sup>73</sup>.

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%<sup>74</sup>, as opposed to draining the battery and fully charging it each time. However, the biggest extensions in lifetime will be 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<sup>76</sup>. 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, the batteries can be stored in a way that optimises climate control as there are less size and weight restrictions.

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

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

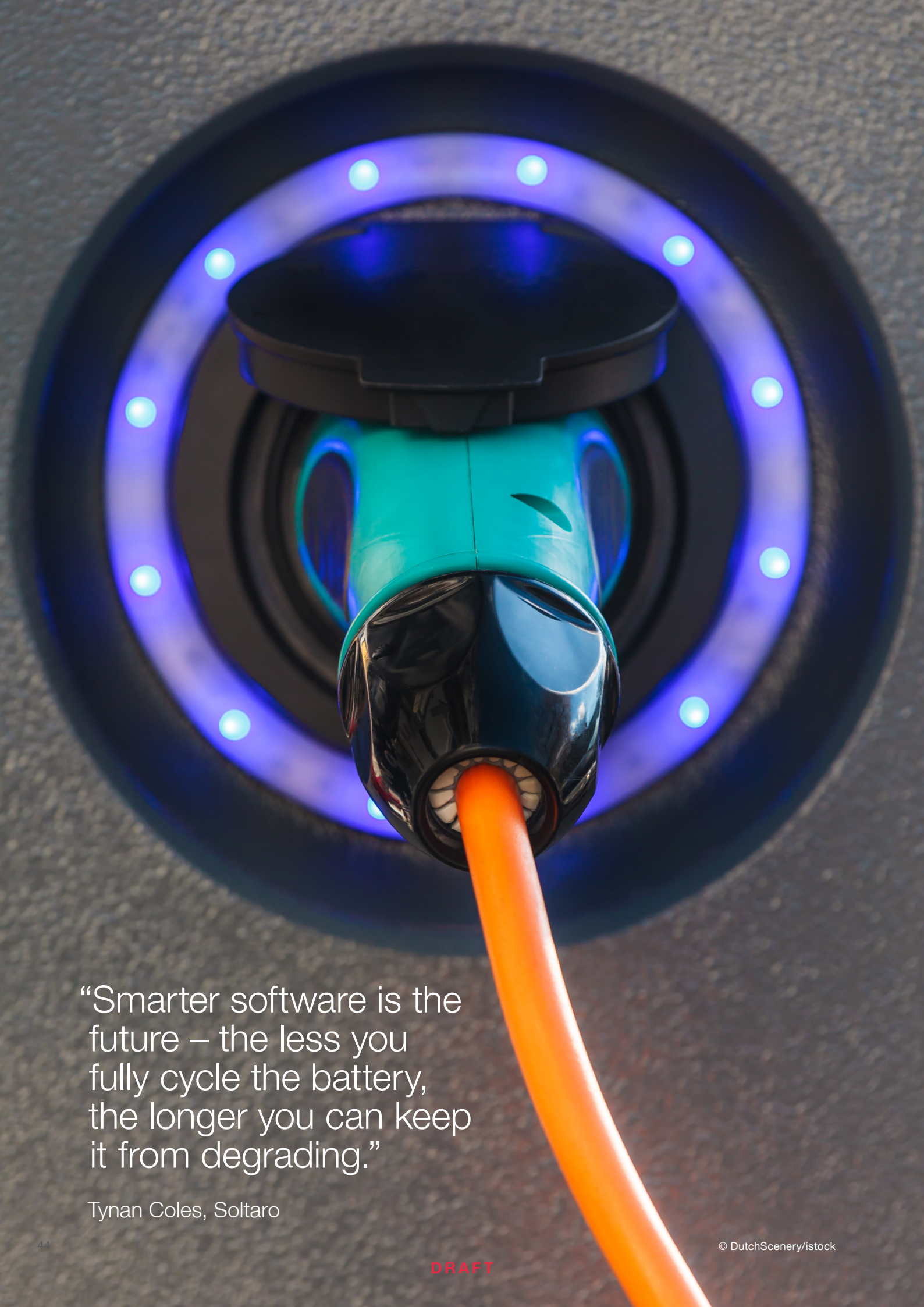
73 Bobba, Mathieux, Blengini, 2019, *How Will Second-Use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-Ion Batteries*

74 [#easyelectriclife Groupe Renault: What is the lifespan of an electric car battery](#)

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

76 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<sup>77</sup>
- China’s biggest operator of telecomms has begun to use second-life LIBs instead of lead acid batteries for back-up power<sup>78</sup>
- Use in buildings – residential, office or industrial applications with no space constraints.

The Johan Cruyff Arena 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<sup>78</sup>.

There will be significant volumes of LIBs available for second life by 2025, as demonstrated in Figure 13. Most will be in China.<sup>79</sup>

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 or 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

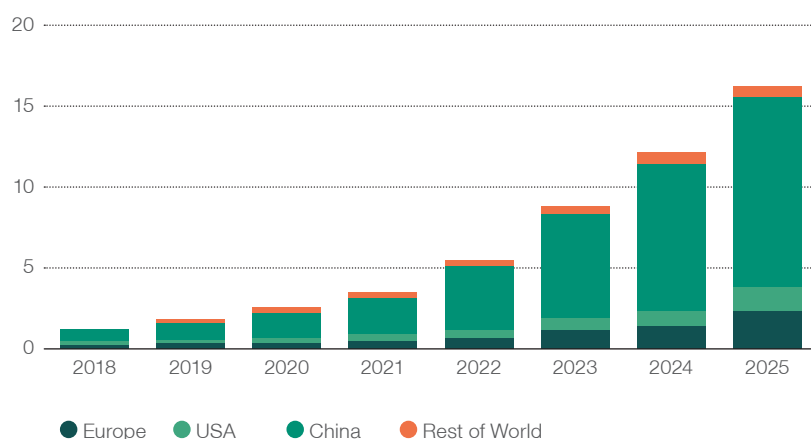


Figure 13: Lithium-ion batteries available for second life by geography (GWh)

cascading their use into alternative uses, rather than reusing LIBs in their original application in EVs.<sup>80</sup>

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.<sup>81</sup> A single market for the second life of batteries would help address the challenges of logistics,<sup>82</sup> by increasing standardisation, awareness and accessibility.

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

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

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

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

81 [Interview – Politecnico].

82 [Interview – Renault Group].



#### CASE STUDY

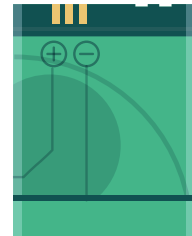
### Renault's Advanced Battery Storage Program

The Program is aiming to build the biggest stationary ESS using EV batteries in Europe at 70 MW/60 MWh<sup>83</sup>, leading the push for large-scale second-life applications.

Renault Group is also developing a SoH protocol for EV batteries<sup>84</sup>. 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 SESS (stationary energy storage systems) in Tumeshima, Japan.



Renault recovers almost 100% of batteries that no longer meet automobile requirements.<sup>85</sup>



#### 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<sup>86</sup>  
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** 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

**A single market for second-hand batteries** to increase standardisation, awareness and accessibility

**Pilots and R&D** on second-life software and optimisation

<sup>83</sup> E-Mob: Circular economy strategies for end-of-life e-mobility batteries

<sup>84</sup> [Interview – Renault Group].

<sup>85</sup> #easyelectriclelife.Groupe.Renault; *A European agreement in favour of the circular economy of the battery/*

<sup>86</sup> Bobba, Mathieux, Blengini, 2019, *How Will Second-Use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-Ion Batteries*





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.





## 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 end-of-life (EOL).*

*This may involve:*

- *Repairing LIBs*
- *Reusing parts of LIBs for new batteries or other applications*
- *Refurbishing LIBs to restore performance.*

Repair is made difficult by the 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 \$2 billion saved in 2030<sup>87</sup>.

Among other EOL strategies is the remanufacturing of the batteries for reuse in the EV or lower performance applications. Remanufacturing is generally seen as the most environmentally friendly of EOL option for a product<sup>88</sup>. 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<sup>88</sup>. 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.

Through research, 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<sup>89</sup>.

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.<sup>90</sup>*

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<sup>91</sup>.

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

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

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

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

91 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<sup>92</sup>
- 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<sup>93</sup>** or collaboration between traditionally separate industries

<sup>92</sup> Bobba, Mathieux, Blengini, 2019, *How Will Second-Use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-Ion Batteries*

<sup>93</sup> Mathur, Deng, Singh, Yih, Sutherland, 2019, *Evaluating the Environmental Benefits of Implementing Industrial Symbiosis to Used Electric Vehicle Batteries*





“If manufacturers would start to collect back their old batteries, they could bring down their costs and have 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<sup>94</sup>.

Battery recycling can provide 13% of the global battery demand for cobalt, 5% of nickel and 9% of lithium in 2030<sup>95</sup>.

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<sup>98</sup>.

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<sup>96</sup>, alongside nickel and copper<sup>97</sup>. 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.

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 different 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.<sup>99</sup>

The lifecycle impacts of pyrometallurgical and hydrometallurgical methods have been studied. One review study 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.<sup>99, 100</sup>

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

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

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

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

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

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

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



Envirostream, a subsidiary of Lithium Australia (who has published patents for a hydrometallurgical recovery process), has successfully conducted a series of recycling trials EV battery packs and expects to ramp up recycling operations.<sup>101</sup>

However, 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<sup>102</sup>.

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<sup>103</sup>.

There are a number of emerging opportunities such as bio-leaching<sup>104</sup>, and pre-recycling steps such as mechanical shredding and size-based sorting<sup>105</sup> and pre-sorting of cathodes<sup>102</sup> 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<sup>103</sup>.

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, or alternatively flexibility in recycling facilities or a variety of facilities, to improve recycling rates
- Uncertainty regarding future dominant chemistries will have an influence over the most appropriate method, whether certain methods become obsolete, and also the viability of recycling, especially if more valuable materials such as cobalt are phased out<sup>104, 105</sup>
- Cost of recycling processes is 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: the purity of materials produced can be low and so applications for recycled materials are reduced
- 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, and these risks can vary depending on location, technologies, processes and mitigations
- Safety concerns: end-of-life LIBs are categorised differently across the world, generally as either 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<sup>105</sup>, though the price of logistics would necessarily rise
- Reducing complexity of logistics should be addressed with other challenges in mind, and careful thought should be given to how to balance safety and performance with travel distances and legislation rigidity.

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

102 Chen, Ho, 2018, *Recovery of Valuable Metals from Lithium-Ion Batteries NMC Cathode Waste Materials by Hydrometallurgical Methods*

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

104 Ordoñez, Gego, Girard, 2015, *Processes and Technologies for the Recycling and Recovery of Spent Lithium-Ion Batteries*

105 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 will be to process it. For this reason, telemetry and materials passports will likely play a key role in the future recycling industry.



## Benefits

Reduces raw material demand and captures currently lost value of used materials

Job creation for waste collectors, pre-treatment companies, waste managers, waste processors and researchers

Environmental impact of end-of-life 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<sup>106</sup>

**Research and development** 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**

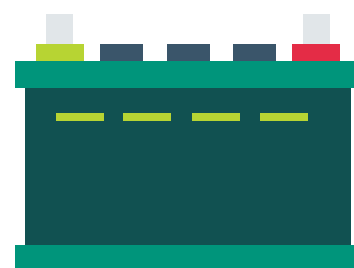


#### CASE STUDY

### 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 impacts of these batteries have 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<sup>107</sup>.



## 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 the 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.

However, there is also another way to look at this challenge. Compelling research is being completed focusing at micro-recycling at the local scale.

This research is being led from 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<sup>108</sup>.

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.

<sup>107</sup> World Economic Forum, Global Battery Alliance, 2019, *A Vision for a Sustainable Battery Value Chain in 2030*

<sup>108</sup> UNSW Sydney: *Smart centers new ARC industrial transformation hub microrecycling battery and consumer wastes*


The storage, treatment, disassembly, recovery, recycling, disposal, and management of the process come 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 ends of the life cycle – either at the start as an upfront recycling fee or at the end as a disposal fee.



## Who bears the cost?

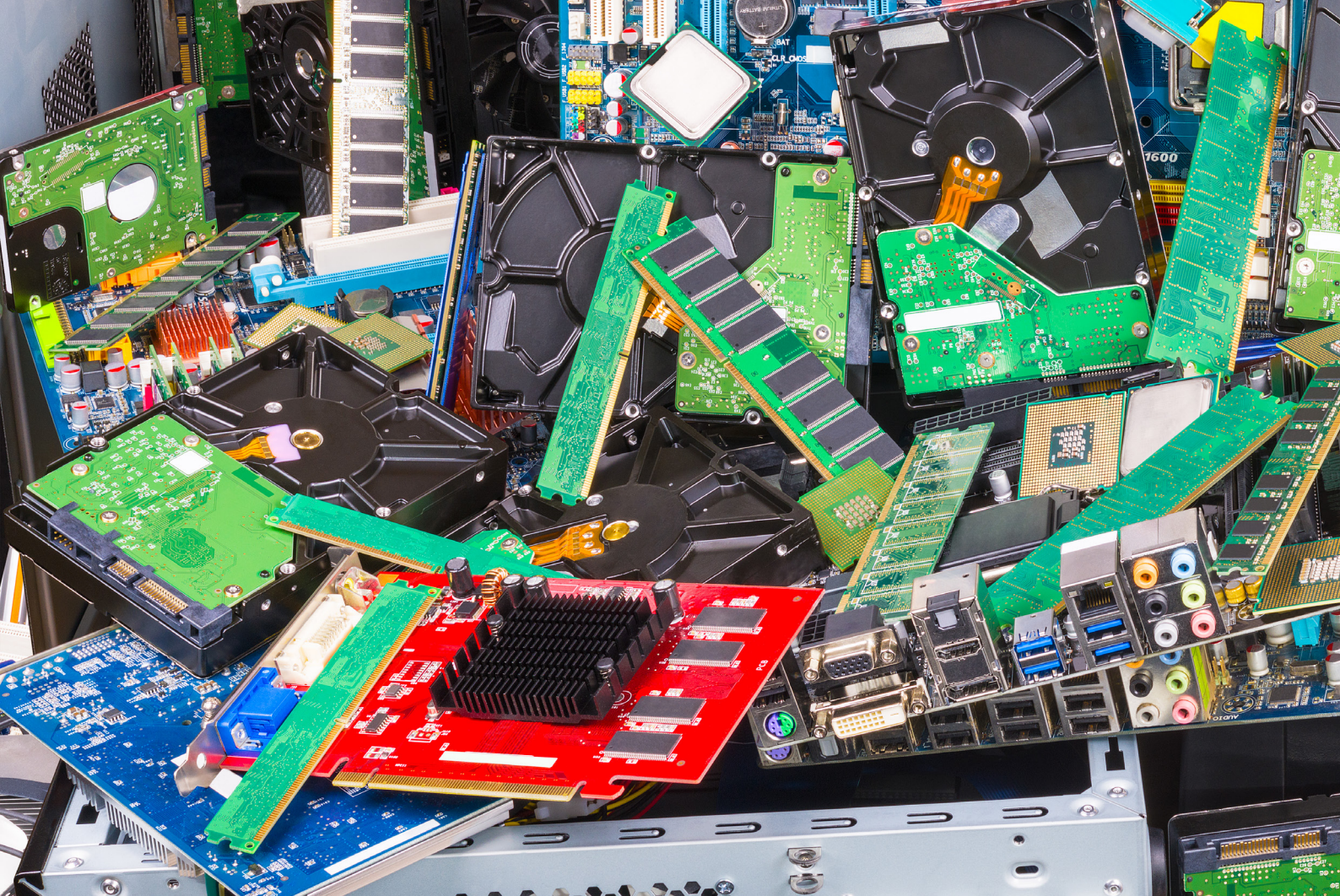
### Producers?

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

### ...and when?

Funding for recycling could either be before use 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 in support of the circular economy, through better re-use of batteries or providing used batteries a second life, which fully complies with the thinking of the 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 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.

In 2018, China adopted its *Interim Measures for the Management of Recycling and Utilisation of Power Batteries of New Energy Vehicles* which implements the EPR principle. Producers are made responsible for labelling and creation of reverse logistics for recycling, leading to new battery recycling companies emerging<sup>109</sup>.

## Recommended Steps

**Policymakers** should foster a supportive regulatory, research and business environment for circular business models 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 other 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 – both new businesses and existing ones

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 coordinate and prioritise investment into most effective CBMs.

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

Coordination and prioritisation of investment into most effective CBM opportunities

Consider the resilience impact and benefits of CBM opportunities

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



**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.

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.





## Polymakers

*Polymakers 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 who is ultimately responsible for LIBs as they move through their life and end-of-life, 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 need to be considered in 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<sup>110</sup>.

<sup>110</sup> 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 a lot of sharing models, both the automotive industry and the grid will have to work together and 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 of 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 policy makers 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<sup>111</sup>.

## 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 end-of-life.

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 end-of-life, and poses challenges for forecasting and predicting future trends”. 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.”<sup>112</sup>*

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, and work with them to implement these solutions across private and public transport systems, and with supportive legislation in place.



Green, social and sustainability bond issuance is set to climb **24% to \$400 billion** this year, reflecting the fact that environmental, social and governance (ESG) considerations are a growing focus for investors.<sup>113</sup>





## Investors

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

### Recommendations

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

Coordination and prioritisation of investment into most effective CBM opportunities

Consider the resilience impact and benefits of CBM opportunities

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

### Impact investment

Currently, and in the absence of government intervention, CBMs typically 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-term time horizon.

There is a niche group of investors, known as impact investors, who are willing 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 up and sold as green investment products, such as green bonds, in the market.

### 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 the principles of a 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 impact to the ecosystem over a long-term time horizon.

Research will continue to play an important role in the transition to a circular economy. Venture capital can help to 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 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 who can 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, research and development, and pilot programs will enable trust and economies of scale to be achieved. Several examples are emerging of collaboration across the supply chain and with government, and should be used to create an evidence base moving forward.

- Renault Group signed up to the French Government's *Circular Economy Roadmap*, focusing on moving towards 100% plastic recycling in France by 2025<sup>114</sup> and has also 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<sup>124</sup>. 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".<sup>115</sup>*

114 Interview – Renault Group

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

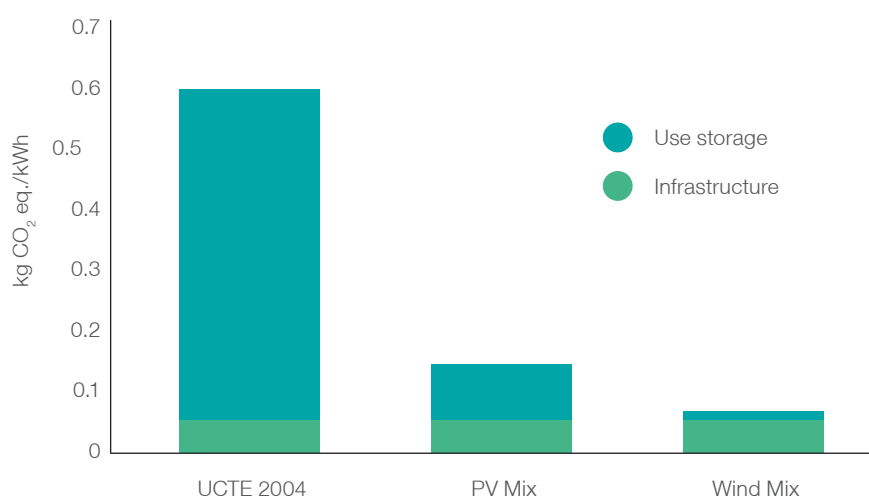
## Decarbonisation

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 the more accessible information about them can be, the more easily processes can be developed to share, test, reuse and disassemble them. Included in design standards should be processes for design for disassembly principles 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 therefore it is important that the industry as a whole discusses the most appropriate approach forward.



**Figure 14:** Overall climate change impacts of a Li-ion battery while using different energy mixes<sup>116</sup>

<sup>116</sup> 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.; Sanfeliix, 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 from 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 the CBMs represent a \$4.5 trillion global growth opportunity that can contribute 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 not compatible 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.

The report aims to harness this opportunity and stimulate circular economy leadership in the LIB industry.

With the industry at 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.

This report has explored how seven focus circular business models could apply to the LIB industry globally to improve its footprint. The seven models that were considered are:



**Product and process design:** rethinking the 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.



**Product as a service:** delivering performance rather than products, where the ownership is retained by the service provider.



**Lifetime extension:** extending the service life of products, through engineering solutions or in 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 end-of-life.



**Recycling:** transforming waste into raw materials to return to the circular supply chain

## Key recommendations

### Policymakers

Implement product stewardship schemes to allocate responsibility for LIBs

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

Work with industry and other governments to facilitate standardisation where appropriate



### Business

Address gaps in information databases to support materials tracking, classify standard modules, and improve testing and forecasting of battery life

Design batteries for cascading reuse and ease of disassembly

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



### Investors

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

Coordinate and prioritise investment into most effective CBM opportunities

Consider the resilience impact and benefits of CBM opportunities

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



### Together

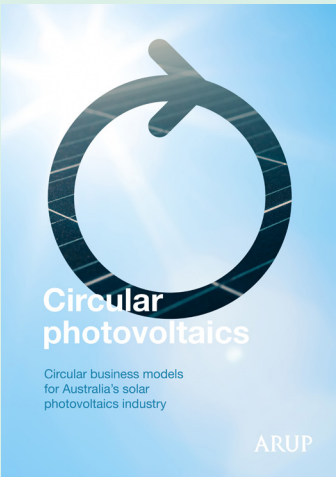
Establish, develop and fast-track partnerships across and outside of the supply chain, and grow global initiatives

Decarbonise production processes and national grids

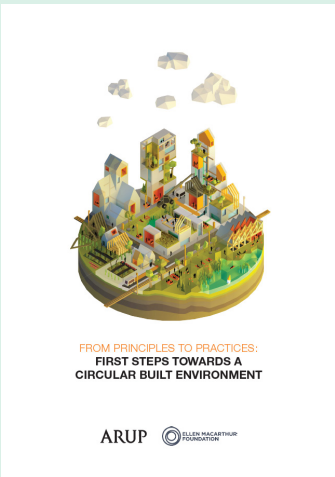
Standardise battery design and data management processes, including labelling and materials passports



Further reading



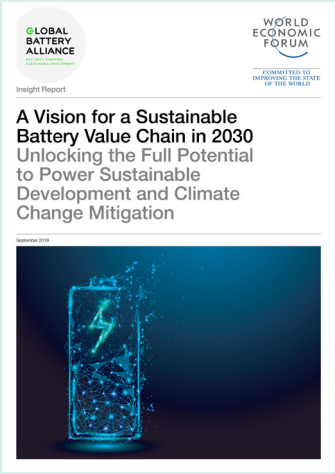
Circular photovoltaics



First steps towards a circular built environment, Arup



Toolkit for Policymakers, Ellen MacArthur Foundation



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

## Glossary

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



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