

Reducing new mining for electric vehicle battery metals: responsible sourcing through demand reduction strategies and recycling

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Research Team

- Elsa Dominish
- Dr Nick Florin
- Dr Rachael Wakefield-Rann

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Inside cover image battery storage using second life-EV batteries at BMW plant in Leipzig. Photo credit: BMW.

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Institute for Sustainable Futures

University of Technology Sydney
PO Box 123 Broadway, NSW, 2007
lithium.isf.uts.edu.au

Executive Summary

Introduction and approach

In order to meet the goals of the Paris Climate agreement and prevent the worst effects of catastrophic climate change, it will be essential for economies to swiftly transition to renewable energy and transport systems. At present, the technologies required to produce, store and utilise renewable energy require a significant amount of materials that are found predominantly in environmentally sensitive and often economically marginalised regions of the world. As demand for these materials increase, the pressures on these regions are likely to be amplified. For renewable energy to be socially and ecologically sustainable, industry and government should develop and support responsible management strategies that reduce the adverse impacts along the material and technology supply chains.

Previous research by the Institute for Sustainable Futures at University of Technology Sydney (ISF UTS), commissioned by Earthworks, into the key areas of concern and opportunities for reform in renewable energy supply chains, highlighted the most urgent and strategic points for priority intervention and research, including:¹

1. **Improve** battery recycling to reduce the demand for materials associated with electric vehicle batteries and other renewable energy technologies.
2. Where supply cannot be met by recycled materials, **source** minerals from certified responsible mining operations.
3. **Avoid** negative impacts in electric vehicle and battery supply chains, intensified by the material intensity of the supply chain, the

severity of impacts, and short battery lifetimes.

Based on these priority areas, this research investigates the current status and future potential of strategies to reduce demand for new mining, particularly for lithium-ion battery metals for electric vehicles. This study is focused on four metals which are important to lithium-ion batteries: cobalt, lithium, nickel and copper.²

There are a range of strategies to minimise the need for new mining for lithium-ion batteries for electric vehicles, including extending product life through improved design and refurbishment for reuse, and recovering metals through recycling at end of life. For example, we found that recycling has the potential to reduce primary demand compared to total demand in 2040, by approximately 25% for lithium, 35% for cobalt and nickel and 55% for copper, based on projected demand. This creates an opportunity to significantly reduce the demand for new mining. However, in the context of growing demand for electric vehicles, it will also be important that other demand reduction strategies with lower overall material and energy costs are pursued in tandem with recycling, including policy to disincentivise private car ownership and make forms of active and public transport more accessible. While the potential for these strategies to reduce demand is currently not well understood; this report provides insights into the relative merits, viability, and implications of these demand reduction strategies, and offers recommendations for key areas of policy action.³

Reuse of batteries in ‘second-life’ applications, recovery of metals for battery manufacturing through recycling and shifts away from private car ownership are key strategies to minimise the need for new mining for EVs batteries.

¹ Dominish, E., Florin, N. and Teske, S., (2019) ‘Responsible Minerals Sourcing for Renewable Energy’. Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney.

² Based on the International Energy Agency’s (IEA) Global EV Outlook 2020 our estimates for future metal demand considers battery electric vehicles (BEVs) and

plug-in hybrid vehicles (PHEVs), across four types of vehicles: passenger light-duty vehicles (PLDVs), light-commercial vehicles (LCVs), buses and trucks.

³ The research timeframe for this analysis was August – December 2020

Key findings

Strategies to reduce metal demand for electric vehicle lithium-ion batteries

This section summarises the most significant findings from each of the three report focal areas: strategies to reduce metal demand for electric vehicle lithium-ion batteries; quantification of potential reductions in primary demand through recycling; and a review of policy gaps and enablers for a circular economy for lithium-ion batteries.

Potential for recovering metals from general end-markets

Mature, industrial-scale recycling of cobalt and nickel currently exists for general end-markets of these metals, achieving global recycling rates above 60%. However, these rates are influenced by the high rates of recycling of super alloys (for cobalt) and stainless steel and nickel and copper based alloys (for nickel), which are typically recycled back into the same product. Other markets for the focus metals are likely to have much lower recycling rates than for batteries. Lithium has low rates of recycling (<1%) and is often used in applications where recovery is difficult. Copper is recycled at an estimated global rate of 45% in a mature process integrated with the production of primary copper, however, there is potential to increase the rate of collection and recycling from certain waste streams.

Potential for recovering metals from end-of-life lithium-ion batteries

Lithium-ion battery recycling is a mature technology; however, current recycling processes are limited in their ability to recover the wide range of elements at a quality suitable for manufacturing new batteries. Most processes only recover the most valuable elements, usually cobalt and often nickel, at a quality suitable for manufacturing cathodes for new batteries. Other metals (including lithium and copper) may end up being recovered for reuse in other industries (downcycled) or lost in the process.

There are a number of established processes capable of recycling lithium-ion batteries at a very large scale and many processes in development. These future processes are designed to recycle cobalt and lithium, and either recycle or downcycle nickel and copper. However, **it is technologically possible to recover all four metals at rates above 90%** and current recovery is limited by the lack of a strong economic driver or policy that could encourage the use of recycled materials.

Potential to use recycled metals in lithium-ion battery manufacturing

A small portion of cobalt and nickel supply in current manufacturing is coming from recycled sources, and there is very little or no lithium being used. Recycled content that does enter the manufacturing process for these three metals is most likely to come from end-of-life lithium-ion batteries, however there are small volumes of metals available from end-of-life lithium-ion batteries compared to the current demand.

There are already some examples of recycling companies working directly with the battery manufacturing supply chain to increase this recovery pathway. Metals recovered from other major end markets are unlikely to be used in lithium-ion battery manufacturing – cobalt and nickel are likely to end up recycled into the same end-use and lithium is usually not recovered. For copper, a more significant portion of supply in manufacturing could come from recycled sources. Copper is most likely to come from other end-markets as secondary copper is processed with primary copper for the smelting and refining stages and copper has not been a priority for recovery in lithium-ion battery recycling.

In future, end-of-life electric vehicle lithium-ion batteries will be the major source for secondary metals for cobalt, lithium and nickel. Even though it is technically possible to recover these metals from other sources, recovering these metals from used lithium-ion batteries back into precursor materials is the most economic route compared to returning them to pure metals from other sources. Copper is likely to come from general copper recycling routes.

Potential for reducing demand for primary materials for lithium-ion batteries for electric vehicles

The demand for new lithium-ion batteries and privately owned electric vehicles that is driving demand for primary battery materials could also be reduced through extension of battery life; refurbishment and reuse in second life applications; and shifts away from private vehicle ownership.

- **Lifetimes:** Current battery lifetimes are estimated between 8 years and 15 years (based on current warranty timeframes and usage data). However, several Original Equipment Manufacturers are working on developing batteries with longer lifetimes, which could reach approximately 20 years. A key limitation to this strategy is that consumers are more likely to upgrade vehicles before batteries reach end-of-life.
- **Reuse:** Reuse schemes allow batteries to have a 'second-life' in a new application once they are no longer considered suitable for use in electric vehicles. Reuse markets are not yet broadly established however some reuse is currently happening; for example, end-of-life batteries are being reused for stationary storage, refurbishment for use in other types of vehicles, and some Original Equipment Manufacturers are looking into electric vehicle -to- electric vehicle applications. The most likely market is the use of end-of-life electric vehicle batteries in grid storage applications, with potential lifetimes of approximately 12 years. These schemes are most likely to be initiated by Original Equipment Manufacturers because the variation between battery design and chemistries limits refurbishment and reuse by third parties.
- **Shifts away from private car ownership:** a move towards public transport, including trains, trams and buses; and active transport, such as bikes, could reduce demand for private car ownership. However, there is currently an absence of the necessary policy and incentives to enable such a shift, particularly in the North American context. Car sharing schemes also have the potential to reduce the number of privately-owned cars, however there are very few examples to date of these working with sufficient uptake to reduce demand for private car ownership-



Quantifying potential reductions in primary demand through recycling

The future demand for cobalt, lithium, nickel and copper was quantified to explore how primary demand could be minimised through changes in recycling, based on the projections of electric vehicle uptake and battery capacity from the International Energy Agency's (IEA) Global electric vehicle Outlook 2020.

This analysis focused on: the contribution of recycled content from general end-markets; the recycling of end-of-life electric vehicle lithium-ion batteries (assuming that it continues at current recovery rates and the recycled content is used in new lithium-ion battery manufacturing); and the additional demand reduction from improving the recovery rates from current rates was quantified and compared to total metal demand. This analysis allowed us to appraise the potential to reduce the demand for new mining. We found that:

- **Recycling has the potential to reduce primary demand compared to total demand in 2040, by approximately 25% for lithium, 35% for cobalt and nickel and 55% for copper. This creates an opportunity to significantly reduce the demand for new mining.**
- For cobalt and nickel, the majority of the reduction in primary demand comes from the use of recycled metals from end-of-life electric vehicle lithium-ion batteries, assuming that recycling continues at current recovery rates, which are already relatively high.
- For lithium, almost all of the reduction in primary demand comes from the use of recycled metals from end-of-life electric vehicle lithium-ion batteries at an improved recovery rate. This is because current recovery rates are low, and lithium is very rarely recovered from other end-markets, and is unlikely to be in future.
- For copper, the use of recycled contents from general end-markets has the most impact on reducing primary demand, followed by the use of recycled metals from end-of-life electric vehicle lithium-ion batteries at an improved recovery rate

This highlights the importance of maintaining the current high recovery rates of cobalt and nickel from electric vehicle lithium-ion batteries recycling as the number of batteries reaching end-of-life grows and improving recovery rates of lithium and copper in lithium-ion batteries recycling. Furthermore, recovering these metals from used lithium-ion batteries back into precursor materials is likely to be the most economic route compared to returning them to pure metals if recovered from other sources. Increasing recovery of copper from other end-of-life products that currently have low rates of recycling will also be important to reduce demand for primary materials.



Effective recycling of end of life batteries has the potential to reduce global demand by 2040 by 55% for copper, 25% for lithium and 35% for cobalt and nickel – creating an opportunity to significantly reduce the demand for new mining.

Review of policy gaps and enablers for a circular economy for lithium-ion batteries

Best practice policies for managing electric vehicle batteries should align with circular economy principles, that prioritise strategies for ensuring decreased material and energy, such as avoidance and reuse, before pursuing recycling and disposal options.

Although many markets, such as the United States and Australia, have or are developing policy or regulatory instruments to encourage the recycling, reuse or refurbishment of consumer electronics and industrial batteries, most markets do not have coordinated policy frameworks targeted specifically for electric vehicle batteries. Policy frameworks required to support the design, collection, transport and logistics, disassembly and other types of processing needed for both reuse and recycling are still underdeveloped across most jurisdictions and action is required now to ensure the systems are in place when the large waste volumes arrive.

The European Union (EU) has made progress towards policies targeted towards electric vehicle batteries that adhere to circular economy principles with a proposal for a new regulation to replace the Batteries Directive. The proposal considers responsible sourcing, mandatory reporting on carbon footprint, and recycled content, as well as measures to address barriers to reuse and information requirements on product durability. Elsewhere policy frameworks remain less developed. Across most jurisdictions, the key policy gaps and enablers include:

- **Collection:** unlike lead-acid batteries, there is currently a lack of mature and consistent take-back pathways for car owners to return their batteries at the end of an electric vehicle's life. It is important that batteries are traceable throughout their lives, and that there is good information sharing along the supply chain, and stakeholder education so adequate collection mechanisms can be established.
- **Transport:** The regulations around transportation and logistics associated with moving end-of-life electric vehicle batteries for both reuse and recycling have been identified as significant barriers, and often relate to the lack of requirements specific to electric vehicle batteries separate from other types of batteries. While the EU is the most advanced in terms of regulating batteries and the proposal for new regulation to replace the Battery Directive aims to address some of the issues, in general the systems established for managing their movement and transport are complex and can lead to perverse outcomes.
- **Design:** electric vehicle batteries are currently manufactured by multiple companies with variations in design, chemistry, size, battery shapes and disassembly requirements, which presents a challenge for recycling. Because electric vehicle batteries are usually not labelled, battery recyclers find it difficult to determine the kind of batteries they are receiving. In addition, because battery management systems are not standardised, consistent approaches cannot be used to test battery health contributing to higher processing costs. This is particularly problematic for testing batteries for reuse. A major barrier to standardisation is the interest of Original Equipment Manufacturers, in maintaining a competitive advantage in the market by protecting specialised information about their lithium-ion battery design. Without standardisation, the most likely reuse applications are direct partnerships between Original Equipment Manufacturers and energy companies.
- **Standards across the battery lifespan:** There is an absence of standards across jurisdictions, which is a barrier to the development of recycling and reuse. These include standards for the performance and durability of first and second life electric vehicle batteries, criteria for what constitutes State of Health and end-of-life, standards for handling of used batteries, criteria for determining suitability of second use applications at end-of-life and labelling of battery composition. New information requirements on performance including durability proposed in the EU is a positive development.
- **Definitions and frameworks:** Definitions of certain terms, particularly "waste" and "reuse", lack the clarity and specificity required to adequately regulate electric vehicle batteries destined for second life and recycling. A review of the policies in the EU found that the lack of clear terms means there is not a clearly defined legal framework within which a market for second life batteries can develop.
- **Quality assurance and liability for second life battery applications:** The uncertainty around liability for damage to, and performance of second-life batteries may be a disincentive for reuse of end-of-life

electric vehicle batteries, compared to new batteries. There are currently no regulatory guarantees regarding the quality of second-life-batteries or performance and very few industry standards for performance specifications for specific applications. It is also unclear in the case that a second-life battery results in damages, whether the Original Equipment Manufacturers are liable. As a result, some Original Equipment Manufacturers are reluctant to allow their EV batteries to be reused in grid storage applications, unless they retain ownership for the duration of their second life, thus retaining the materials for their potential recycling value and maintaining liability.

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Glossary

BEV	Battery electric vehicle
BMS	Battery management system
CAM	Cathode active material
EOL	End-of-life
EPR	Extended Producer Responsibility
EU	European Union
ELV	End-of-life vehicle
EV	Electric vehicle
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt hours
IEA	International Energy Agency
LCV	Light commercial vehicle
LFP	lithium iron phosphate (type of LIB)
LIB	lithium-ion battery
LCO	lithium cobalt oxide (type of LIB)
LMO	lithium manganese oxide (type of LIB)
MSW	Municipal solid waste
NMC	Nickel manganese cobalt (type of LIB)
NCA	Nickel cobalt aluminium (type of LIB)
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PHEV	Plug-in hybrid electric vehicle
PLDV	Passenger light duty vehicle
SOH	State of health
PV	Photovoltaic
WEEE	Waste Electrical & Electronic Equipment

Introduction

In order to meet the goals of the Paris Climate agreement and prevent the worst effects of catastrophic climate change, it will be essential for economies to move to renewable energy and transport systems. The transition to renewable systems is well underway, with rapidly growing demand for electric vehicles (EVs), projected to reach between 4.5 and 7 million vehicles per year by 2030.⁴

At present, the technologies required to produce, store and utilise renewable energy require significant amounts of materials that are found predominantly in environmentally sensitive and often economically marginalised regions of the world. As demand for these materials increase, the pressures on these regions are likely to be amplified, risking the goals of a socially and ecologically sustainable renewable energy system. New mining projects are already underway, particularly for battery metals including cobalt, lithium, nickel and copper. These projects have the potential for adverse impacts on local environments and communities, including pollution of soil, air and water, human rights abuses and unsafe working conditions.⁵

Previous research by the Institute for Sustainable Futures at University of Technology Sydney (ISF UTS), commissioned by Earthworks, into the key areas of concern and opportunities for reform in renewable energy supply chains, highlighted the most urgent and strategic points for priority intervention and research, including:⁶

1. **Improve** battery recycling to reduce the demand for materials associated with electric vehicle batteries and other renewable energy technologies.
2. Where supply cannot be met by recycled materials, **source** minerals from certified responsible mining operations.
3. **Avoid** negative impacts in electric vehicle and battery supply chains, intensified by the material intensity of the supply chain, the severity of impacts, and short battery lifetimes.

Based on these priority areas, this research investigates the current status and future potential of strategies to reduce demand for new mining, particularly for lithium-ion battery (LIB) metals for EV. This study is focused on four metals which are important to LIBs: cobalt, lithium, nickel and copper.

There are a range of strategies to minimise the need for new mining for LIBs for EVs, including extending product life through improved design and refurbishment for reuse, and recovering metals through recycling at end-of-life (EOL), as well as shifts away from private car ownership towards shared vehicles or active and public transport.

However, the relative potential for these strategies to reduce demand is currently not well understood. For example, it is unclear within current LIB recycling processes what proportion of metals can be recovered at a quality suitable for the manufacturing of new LIBs. It is also not known if recycled metals from other end-markets might be recovered to a grade that is suitable for the production of new energy technologies. Although many recycling systems are being developed and deployed for LIBs, only a very small number of LIBs from EVs have reached EOL, estimated to be less than 150,000 vehicles in 2020.⁷

Current LIB recycling processes (for all end-uses) only focus on the recovery of metals with the highest economic value, particularly cobalt and nickel, while other metals may end up being downcycled or lost in the process. However, new recycling technologies targeting the recovery of a wider range of materials, including lithium, are being developed. This is driven by manufacturer, government and consumer concerns about the management of LIBs at EOL, the supply of raw materials for manufacturing and the impacts of new mining. As greater priority is given to a circular economy approach, novel reuse strategies are also being developed

⁴ Based on our analysis of the International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>

⁵ Dominish, E., Florin, N. and Teske, S., (2019) 'Responsible Minerals Sourcing for Renewable Energy'. Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney.

⁶ Ibid

⁷ Based on our analysis of the International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>

and deployed; although, given that these are in early stages, little is known about the potential impact of these strategies. This report provides insights into the relative merits, viability, and implications of these demand reduction strategies, and provides recommendations for key areas of policy action.

Project scope and objectives

This research investigates the current status and future potential of these strategies to reduce demand for new mining for LIBs for EVs. We focus on four metals which are important to LIBs: cobalt, lithium, nickel and copper. The objectives of this study are to understand:

- the potential for recovering metals from EOL LIB and other products suitable for manufacturing of LIBs;
- the potential to minimise demand for primary materials used in LIB and EVs;
- the impact of these strategies on projected demand for minerals for the renewable energy transition;
- the effectiveness of minerals recycling and reuse policies.

Approach

The approach for this study was to undertake a literature review and conduct semi-structured interviews with battery supply chain experts. Based on this, scenarios were developed for quantitative material flow modelling. This was carried out to examine the impact of recycling strategies on the projected demand for EV metals.

Interviews were undertaken with the following stakeholders:

Organisation	Role in LIB battery supply chain
BASF	Cathode active materials manufacturer
Umicore	Cathode active materials manufacturer and LIB recycler
Envirostream	LIB recycler
BMW	EV OEM
General Motors	EV OEM
Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia	Research
University of California, Davis (UC Davis)	Research
Technische Universität Braunschweig (TUB)	Research

Report overview

The research findings are presented in the following sections:

- Part 1: Strategies to reduce metal demand for EV LIBs, including:
 - The potential for recovering metals from EOL LIB and general end markets
 - The potential to use recycled metals in LIB manufacturing
 - The potential for reducing demand for LIBs and EVs
- Part 2: Quantifying potential reductions in primary demand through recycling
- Part 3: Review of policy gaps and enablers for a circular economy for LIBs

Key definitions

Downcycling

Downcycling may use the same processes as recycling, however, the material is recovered for other uses and not at a quality suitable for battery manufacturing. Based on circular economy principles, this option is less desirable than reuse and recycling.

Electric Vehicle

Based on the International Energy Agency's (IEA) Global EV Outlook 2020 our estimates for future metal demand considers battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), across four types of vehicles: passenger light-duty vehicles (PLDVs), light-commercial vehicles (LCVs), buses and trucks. We acknowledge that there are other types of electric vehicles that will likely become more important in the future, such as electric bikes, but they are out of the scope of this study.

End-of-Life

For the purposes of this report, a product or component is considered to reach EOL when it ceases to be used for a given purpose and is either disposed of, disassembled for recycling, or reused in another type of product or application.

Extended Producer Responsibility

The OECD defines Extended Producer Responsibility (EPR) as “an environmental policy approach in which a producer’s responsibility for a product is extended to the post-consumer stage of a product’s life cycle”.

Producer responsibilities go beyond worker safety and pollution from manufacturing and include management at EOL.

Reuse and Refurbishment

Reuse and refurbishment as applied to EV batteries generally involves the testing of battery modules to determine which ones are degraded and their replacement with modules from other batteries that are still serviceable. The batteries can then have a “second life” in another product.

Recycling

In the context of batteries, recycling refers to any form of processing (e.g.: mechanical, pyrometallurgical, hydrometallurgical) that involves the dismantling of a battery and the recovery of its constituent materials, such as metals, for use in the same or other applications. Recycling implies the material recovery is achieved at approximately the same value as the original, i.e. recovery at a quality suitable for battery manufacturing.

Part 1: Strategies to reduce metal demand for electric vehicle lithium-ion batteries

Potential for recovering metals from general end-markets

The following section presents an overview of the four metals which are the focus of this study, including their major end markets, projected future demand and maturity of recycling systems.

Cobalt

Major end markets:

LIBs (for all applications) are the major end market for cobalt (see Table 1). The share of demand for LIBs varies across different sources, with estimates including from 28% in 2017 and a projection of 53 – 61% in 2025,⁸ compared to an estimation of 57% in 2018.⁹ Other major end markets include superalloys, tools and hard metals.

Table 1: Cobalt end markets

Major end markets	Share of demand (2017) ¹⁰	Share of demand (2025)
All batteries	28%	53 – 61%
Superalloys	26%	16 – 20%
Tools and hard materials	15%	5 – 8%
Others	31%	18 – 22%

LIB EV market:

Of the cobalt used in LIB, more than 63% is consumed as cobalt oxide which is typically used in batteries for electronics and 37% as cobalt sulphate which is used in LIBs for EVs.¹¹ Therefore, based on the share cobalt demand for all batteries estimated above in 2017/18, we can assume 10 – 21% of total cobalt was used in LIBs for EVs in this period.

As the uptake of EVs continues to grow, it is expected that the share of demand of cobalt for all LIBs will rise. It is also expected that EVs will have a higher share of LIB battery demand than electronics, with Roskill forecasting that EVs will exceed 90% of the global LIB capacity demand by 2023.¹² This represents a significant uptick in the share of LIB battery demand from EVs. Based on the assumption that total cobalt demand by 2025 could reach approximately 60% for all LIBs, we can assume that cobalt demand for EV LIBs could be more than 50% of total cobalt demand.

Future demand: It is estimated that cobalt demand will grow by close to 10% per year until 2025. This demand is mainly due to EV LIBs, however most other uses are expected to increase at a slower rate (3% per year or less), while some applications may decline (e.g. magnets).¹³

⁸ McKinsey., 2018. lithium and cobalt - a tale of two commodities. Available at: <https://lithium.mckinsey.com/~media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx>

⁹ Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

¹⁰ McKinsey., 2018. lithium and cobalt - a tale of two commodities. Available at: <https://lithium.mckinsey.com/~media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx>

¹¹ Roskill., 2019. lithium-ion Batteries: Outlook to 2028. 3rd ed. London: Roskill Information Services – cited in Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

¹² Roskill., 2019. Batteries: New mobility demands see renewed emphasis on raw material sustainability in the EU <https://roskill.com/news/batteries-new-mobility-demands-see-renewed-emphasis-on-raw-material-sustainability-in-the-eu/>

¹³ McKinsey., 2018. Metal mining constraints on the electric mobility horizon. Available online at: <https://lithium.mckinsey.com/industries/oil-and-gas/our-insights/metal-mining-constraints-on-the-electric-mobility-horizon>

Maturity of recycling:

Cobalt scrap is often recycled, but for super alloys which are the major end-market, it is likely to be recycled back into the same use rather than general recycling streams.¹⁴ Cobalt from LIB used in electronic items is likely to be recycled to cobalt tetroxide for use in LCO batteries to be used again in electronics.

Recycling rates:

Global recycling rates are estimated to be approximately 68%, however, this is likely to vary widely across products.¹⁵

Recycled content:

Global recycled content is estimated at approximately 32%.¹⁶ For LIB (for all end-uses) McKinsey assume that 8.5 – 12% of cobalt refined metal is from recycled sources in 2017, and this would decrease to 7.5 – 10% in 2025.¹⁷ Umicore estimate 9.2% of their 2019 cobalt supply is from secondary sources.¹⁸

Lithium

Major end markets:

LIBs (for all end-uses) are the major end-use for lithium, followed by glass / ceramics and industrial uses (see Table 2). The share of lithium demand for LIBs varies across different sources, with estimates including 41% in 2017 and a projection of 76 – 82% in 2025,¹⁹ compared to an estimation of 65% in 2019.²⁰

Table 2: lithium end markets

Major end markets	Share of demand (2017) ²¹	Share of demand (2019) ²²	Share of demand (2025) ²³
All batteries	41%	65%	76 – 82%
Glass and ceramics	23%	18%	7 – 9%
Industrial and other uses	36%	17%	11 – 15%

¹⁴ U.S. Geological Survey (USGS), 2020. Mineral commodity summaries 2020: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

¹⁵ UNEP., (2011), Recycling Rates of Metals – A Status Report. A Report of the Working Group on Global Metal Flows to the International Resource Panel. Graedel, T.E; Allwood, J; Birat, J-P; Reck, B.K; Sibley, S.F; Sonnemann, G; Buchert, M; Hagelüken, C. Available at: <https://lithium.resourcepanel.org/reports/recycling-rates-metals>

¹⁶ Ibid

¹⁷ McKinsey., (2018). lithium and cobalt - a tale of two commodities. Available at: <https://lithium.mckinsey.com/~media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx>

¹⁸ Umicore (2019) Due Diligence Compliance Report Cobalt Procurement 2019, <https://lithium.umicore.com/en/about/sustainability/due-diligence-compliance-report-cobalt-procurement>

¹⁹ McKinsey., 2018. lithium and cobalt - a tale of two commodities. Available at: <https://lithium.mckinsey.com/~media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx>

²⁰ Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbirc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

²¹ McKinsey., (2018). lithium and cobalt - a tale of two commodities. Available at: <https://lithium.mckinsey.com/~media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx>

²² U.S. Geological Survey (USGS), 2020. Mineral commodity summaries 2020: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

²³ McKinsey., (2018). lithium and cobalt - a tale of two commodities. Available at: <https://lithium.mckinsey.com/~media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx>

LIB EV market:

Although projections of the market are given for LIBs for all end-uses rather than for EVs, as with cobalt, it is expected that EVs will have a higher share of LIB battery demand than electronics, with Roskill forecasting that EVs will exceed 90% of global LIB capacity demand by 2023.²⁴

Future demand:

Lithium demand is projected to grow at 14.6% per year until 2025, the fastest of all battery metals. This growth will be predominantly from LIB, while other uses are expected to grow at approximately 2% per year.²⁵ In 2019 Roskill predicted an annual growth rate for lithium hydroxide demand in rechargeable batteries of 35.3% from 2018 to 2028.²⁶

Maturity of recycling:

Lithium has very low rates of recycling, partly driven by the fact that lithium is often used in applications where recovery is difficult and uneconomical.

Recycling rates:

Recycling rates of lithium are unknown but estimated to be less than 1%.²⁷

Recycled content:

Recycled content is also unknown and estimated to be less than 1%.²⁸

Nickel

Major end markets:

The end-markets for nickel are given as a share of first-use (the type of nickel product) and a share of end-use (the sector that the product is applied in) (see Table 3). More than 70% of nickel is used in stainless steel, which is used across various end-markets.

Table 3: Nickel end markets

Product type	Share of first-use ²⁹	Major end markets	Share of end-use ³⁰
Stainless steel	70%	Engineering	35%
Ni and Cu base alloys	8%	Metal goods	19%
Alloy steels and castings	8%	Transport	16%
Plating	8%	Building and construction	15%
Batteries	5%	Electronics	11%
Other	1%	Others	4%

²⁴ Roskill., 2019. Batteries: New mobility demands see renewed emphasis on raw material sustainability in the EU <https://roskill.com/news/batteries-new-mobility-demands-see-renewed-emphasis-on-raw-material-sustainability-in-the-eu/>

²⁵ McKinsey., (2018). Metal mining constraints on the electric mobility horizon. Available online at: <https://lithium.mckinsey.com/industries/oil-and-gas/our-insights/metal-mining-constraints-on-the-electric-mobility-horizon>

²⁶ Roskill., 2019. lithium-ion Batteries: Outlook to 2028. 3rd ed. London: Roskill Information Services – cited in Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

²⁷ UNEP., (2011), Recycling Rates of Metals – A Status Report. A Report of the Working Group on Global Metal Flows to the International Resource Panel. Graedel, T.E; Allwood, J; Birat, J-P; Reck, B.K; Sibley, S.F; Sonnemann, G; Buchert, M; Hagelüken, C. Available at: <https://lithium.resourcepanel.org/reports/recycling-rates-metals>

²⁸ Ibid

²⁹ Nickel Institute (n.d.) <https://nickelinstitute.org/about-nickel/#firstuse>

³⁰ Nickel Institute (n.d.) <https://nickelinstitute.org/about-nickel/#enduse>

LIB EV market:

The use of nickel in lithium-ion batteries for EVs is a small share of the total market, although it is projected to grow.

Future demand:

Nickel demand is projected to grow. Studies have estimated that demand could reach 3.1 million metric tonnes in 2030, up from approximately 2 million tonnes in 2020.³¹

Maturity of recycling:

Nickel used in stainless steel or alloys is typically recycled back into the same end-markets at a high rate. The majority of nickel that ends up in landfill is from metal goods and waste electrical and electronic equipment.³²

Recycling rates:

It is estimated that approximately 68% of nickel from EOL consumer products is recycled and another 15% enters the carbon steel loop.³³

Recycled content:

Global recycled content is estimated to be between 29 and 41%.³⁴ In the US, it is estimated that recycled nickel accounts for 47% of primary consumption. In particular, stainless steel, and nickel and copper based alloys are recycled at a high rate (with an estimated 66% of stainless steel consumption from secondary sources). For other applications (including batteries, catalysts, coinage and other alloys), the secondary sources are estimated to be 43% of nickel consumption.³⁵

It is estimated that 20-25% of nickel sulphate (used for cathode manufacturing) is from recycled sources in 2019/2020, although it is not known what percentage is suitable for LIB manufacturing.³⁶

Copper

Major end markets:

Building and construction and infrastructure are the major end markets for copper, accounting for more than 70% of metal in use (see Table 4). The average expected lifetime of copper products is about 25 years.³⁷ For plumbing or industrial infrastructure, the lifetime is estimated to be 40-50 years, whereas consumer electronic equipment is likely to have a shorter lifetime of less than 10 years.³⁸

³¹ Watari, T., Nansai, K. and Nakajima, K., Major metals demand, supply, and environmental impacts to 2100: A critical review. *Resources, Conservation and Recycling*, 164, p.105107.

³² Nickel Institute (n.d.) <https://nickelinstitute.org/policy/nickel-life-cycle-management/nickel-recycling/>

³³ Ibid

³⁴ UNEP., (2011), Recycling Rates of Metals – A Status Report. A Report of the Working Group on Global Metal Flows to the International Resource Panel. Graedel, T.E; Allwood, J; Birat, J-P; Reck, B.K; Sibley, S.F; Sonnemann, G; Buchert, M; Hagelüken, C. Available at: <https://lithium.resourcepanel.org/reports/recycling-rates-metals>

³⁵ U.S. Geological Survey (USGS), 2020. 2016 Minerals Yearbook: Nickel. Available at: <https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-nickel.pdf>

³⁶ Roskill., 2019. Lithium-ion Batteries: Outlook to 2028. 3rd ed. London: Roskill Information Services – cited in Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

³⁷ Glöser, S., Soulier, M. and Tercero Espinoza, L.A., 2013. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. *Environmental Science & Technology*, 47(12), pp.6564-6572.

³⁸ Spataro, S., Bertram, M., Gordon, R.B., Henderson, K. and Graedel, T.E., 2005. Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics*, 54(1), pp.37-51.

Table 4: Copper end markets

Major end markets	Share of demand ³⁹	Share of in-use stock ⁴⁰
Building construction	28%	50%
Infrastructure	17% (including power and telecommunications)	22%
Transport	13%	5%
Other	32% (including general consumer products 9%, cooling 8%, electronic products 5%)	23%

LIB EV market:

The use of copper in lithium-ion batteries for EVs is a small percentage of the total copper market, although it is projected to grow. Copper is used in LIBs as a copper foil. Batteries (of all kinds) make up an estimated 20% of the high-end copper foil market, which is dominated by demand for circuit boards.⁴¹

Future demand:

Studies have estimated that copper demand could reach 40 million metric tonnes in 2030,⁴² up from 23.8 Million Metric Tons in 2020.⁴³ Copper is difficult to substitute in most applications. The exception to this is aluminium in some automotive and electrical applications, titanium and steel can in heat exchangers, optical fibres in telecommunications and plastics in plumbing applications.⁴⁴

Maturity of recycling:

Copper recycling is a mature process that is integrated with the production of primary copper.⁴⁵ There are two main ways of processing primary copper depending on the ore. The pyrometallurgical process is the main process route, accounting for more than 80% of production and is used for processing sulphidic ores. The process involves three main steps: crushing and flotation to produce a concentrate, smelting to remove the iron and sulphur fractions, and electrolytic refining to further remove impurities and produce a copper cathode. Copper containing scrap is added during the smelting stages, so that primary and secondary copper are combined for both the smelting and refining stages.⁴⁶

Although recycling is mature there is clear scope to increase the rate of collection (greater than 50% is not recovered) and recycling (global average is estimated to be 45%). In particular the separating, sorting and disassembly of copper could be improved from waste electronic and electrical equipment (WEEE), EOL vehicles (ELV) and municipal solid waste (MSW).⁴⁷

³⁹ Copper Alliance in Henckens, M.L.C.M. and Worrell, E., 2020. Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. *Journal of Cleaner Production*, p.121460.

⁴⁰ Schipper, B.LITHIUM., Lin, LITHIUM.C., Meloni, M.A., Wansleeben, K., Heijungs, R. and van der Voet, E., 2018. Estimating global copper demand until 2100 with regression and stock dynamics. *Resources, Conservation and Recycling*, 132, pp.28-36.

⁴¹ <https://lithium.mordorintelligence.com/industry-reports/high-end-copper-foil-market>

⁴² Watari, T., Nansai, K. and Nakajima, K., Major metals demand, supply, and environmental impacts to 2100: A critical review. *Resources, Conservation and Recycling*, 164, p.105107.

⁴³ https://lithium.reportlinker.com/p0459175/Global-Copper-Industry.html?utm_source=PRN

⁴⁴ U.S. Geological Survey (USGS), 2020. Mineral commodity summaries 2020: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

⁴⁵ Glöser, S., Soulier, M. and Tercero Espinoza, L.A., 2013. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. *Environmental Science & Technology*, 47(12), pp.6564-6572.

⁴⁶ Ibid

⁴⁷ Ibid

Recycling rates:

The estimated recycling rate for copper from EOL products varies by product and by region. Glöser et al (2013) estimate an average global recycling rate of 45%.⁴⁸ Based on this estimate, Henckens and Worrell (2020) map the fate of EOL copper products (

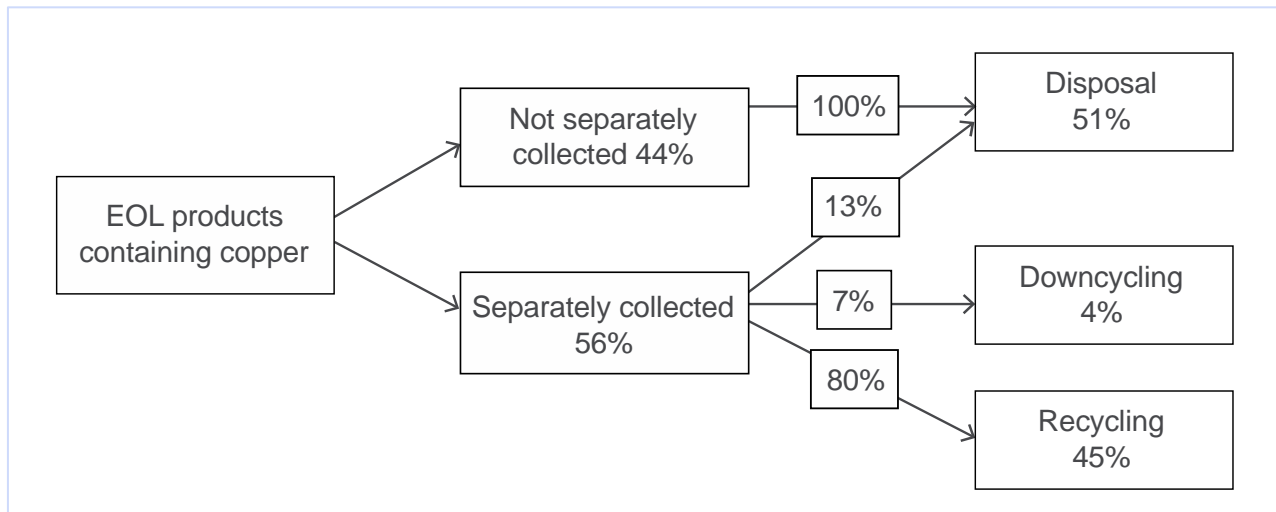


Figure 1).⁴⁹ This shows that 44% of copper in EOL products is not separately collected, and when this is combined with losses during recycling, more than 50% of copper in EOL products is not recovered. 45% of copper in EOL products is recycled and 4% is downcycled to the aluminium and steel loops.

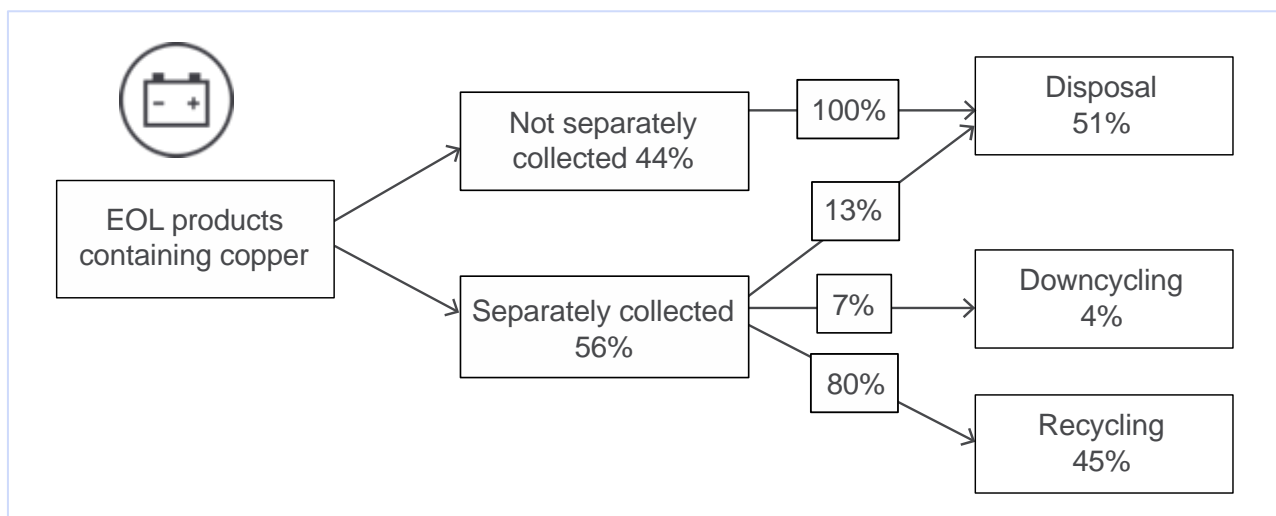


Figure 1: Fate of copper in EOL copper products⁵⁰

Recycled content rates:

It is estimated that about one third of total global demand is met by recycled copper, including new and old scrap.⁵¹ The majority of copper in-use stock is in applications with long lifetimes, which limits the availability of recycled copper to meet demand for new copper products.

⁴⁸ Glöser, S., Soulier, M. and Tercero Espinoza, L.A., 2013. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. *Environmental Science & Technology*, 47(12), pp.6564-6572.

⁴⁹ Henckens, M.L.C.M. and Worrell, E., 2020. Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. *Journal of Cleaner Production*, p.121460.

⁵⁰ Figure adapted from Henckens, M.L.C.M. and Worrell, E., 2020. Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. *Journal of Cleaner Production*, p.121460.

⁵¹ Glöser, S., Soulier, M. and Tercero Espinoza, L.A., 2013. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. *Environmental Science & Technology*, 47(12), pp.6564-6572.

Summary of markets and recycling for cobalt, copper, lithium and nickel

Table 5: Summary of metal markets

	Major end markets	LIB EV market	Future demand	Maturity of recycling
Cobalt	LIB (for all end-uses) are the major end-use, followed by super alloys.	In 2018 total LIB estimated to be 57% of market. We can assume 21% of cobalt is used in LIB for EVs and stationary storage and 36% is LIB for electronics.	Projected to grow by close to 10% per year until 2025. Mainly due to LIB for EVs, however most other uses are expected to increase at a slower rate while some applications may decline.	Often recycled with a global recycling rate of 68%, super alloys are recycled at a high rate.
lithium	LIB (for all end-uses) are the major end-use, followed by glass / ceramics and industrial uses.	LIB market estimated to be 65% in 2019.	Projected to grow at 14.6% per year until 2025. Predominantly from LIB for EVs, while other uses are expected to grow at approximately 2% per year	Low rates of recycling <1%.
Nickel	Stainless steel 70% and alloys 16% of first use.	Very small share of total market (% unknown).	Projected to grow.	Often recycled with a global recycling rate of 68%, stainless steel and nickel and copper based alloys are recycled at a high rate.
Copper	Building construction 28% of use and 50% of in-use stock, infrastructure 17% of use and 22% of in-use stock.	Very small share of total market (% unknown).	Projected to grow, majority of copper in-use stock in applications with long lifetimes, which limits recycling and difficult to substitute in most applications.	Often recycled at an estimated global rate of 45% in a mature process integrated with the production of primary copper. There is potential to increase the rate of collection and recycling particularly from the WEEE, ELV and MSW streams.

Potential for recovering metals from end-of-life lithium-ion batteries

LIB recycling is a relatively mature technology that has been developed targeting LIBs used for electronics. However, there are significant material losses as current recycling processes are limited in their ability to recover the wide range of elements at a quality suitable for manufacturing new batteries. Because recycling processes are complex and very resource intensive, only the most valuable elements are targeted for recovery. Most processes recover valuable cobalt and often nickel as metal or salt suitable for cathode manufacturing. Other metals (particularly copper, aluminium and steel) are often recovered for use in other metal industries (downcycled) or may be lost in the process.⁵²

In general, there are four broad steps involved in the recycling process that are variously applied (Figure 2), including:⁵³

(i) discharge and disassembly: this step is typically done manually and involves removal of plastic or metal covers and copper cables. Passivation can be achieved with the recovery of the remaining charge; however most large-scale recycling processes do passivation “in process”;

(ii) mechanical pre-processing: this step involves shredding and grinding to recover the mixed metal oxides present in the electrodes and in solution, and to separate out the plastic. Typically, the valuable mixed metal oxides (Co, Ni, Li, Mn) end up in a mixture of finer particles known as the “black mass” and these materials may be separated from the metal foils (Cu) and plastic during pre-processing;

(iii) pyrometallurgical processing: this processing step uses high-temperatures to concentrate the valuable materials in a mixed metal alloy containing Co, Ni and Cu. The Li and Mn end up in a slag that may be used in construction industries, or Li can be recovered through further processing, including hydrometallurgical;

(iv) hydrometallurgical processing: this a chemical processing step that uses solvents to remove impurities and separate Li, Ni and Co from the “black mass” to achieve a quality suitable for battery manufacturing.

There are a number of established processes capable of recycling LIBs at very large scale, processing volumes greater than 1000 tonnes per year; however, there does not appear to be a single dominant recycling pathway (see Table 6). This is in part owing to an increasing variety of LIB chemistries comprised of different materials, as well as the trade-offs in terms of energy and material inputs, and the quality of the recovered materials. Typically, an overall material recovery rate of 40-60% is achieved with major losses including plastic, graphite and electrolyte.⁵⁴ In general, recovery efficiency increases with processing complexity because more processing steps are needed to recover a wider range of materials.

Table 6 provides a summary of the LIB recycling processes drawing on information from published literature.^{55,56} Here, the recycling processes are categorised as ‘established LIB recycling processes’ where LIBs are the major input; ‘other industrial processes’ processes that are mature e-scrap recycling processes accepting LIBs; and, ‘emerging’ processes that are new technologies designed for LIB recycling that are not yet operating commercially.⁵⁷

Table 6 includes the process route and capacity and the assumed end-market by metal (for the metals in focus for this study). Note, we define recycling as metal recovery to a quality suitable for battery

⁵² Velázquez-Martínez, O., Valio, J., Santasalo-Aarnio, A., Reuter, M. and Serna-Guerrero, R., 2019. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries*, 5(4), p.68

⁵³ International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>

⁵⁴ Bartosinski, M. (2017) Processing of spent Li-ion batteries: Environmental challenges, ICBR Lisbon September, 2017

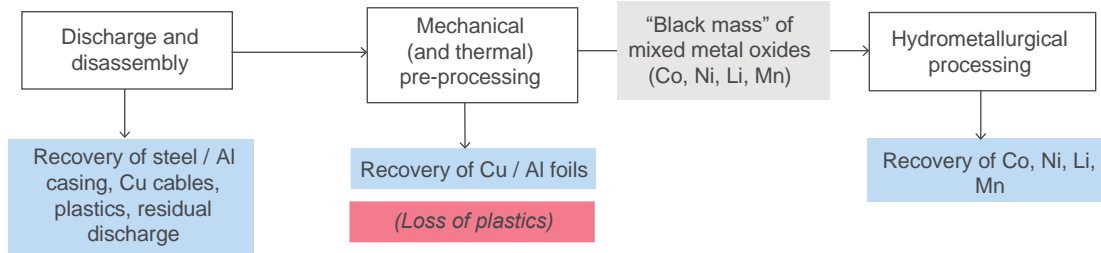
⁵⁵ Velázquez-Martínez, O., Valio, J., Santasalo-Aarnio, A., Reuter, M. and Serna-Guerrero, R., 2019. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries*, 5(4), p.68

⁵⁶ International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>

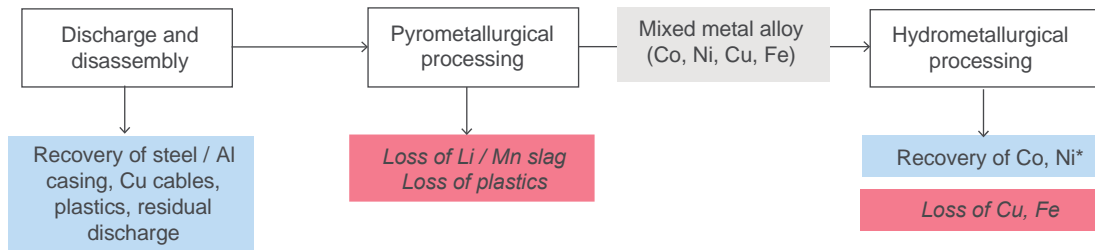
⁵⁷ Velázquez-Martínez, O., Valio, J., Santasalo-Aarnio, A., Reuter, M. and Serna-Guerrero, R., 2019. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries*, 5(4), p.68

manufacturing, and downcycling as recovery for other uses and not at a quality suitable for battery manufacturing.

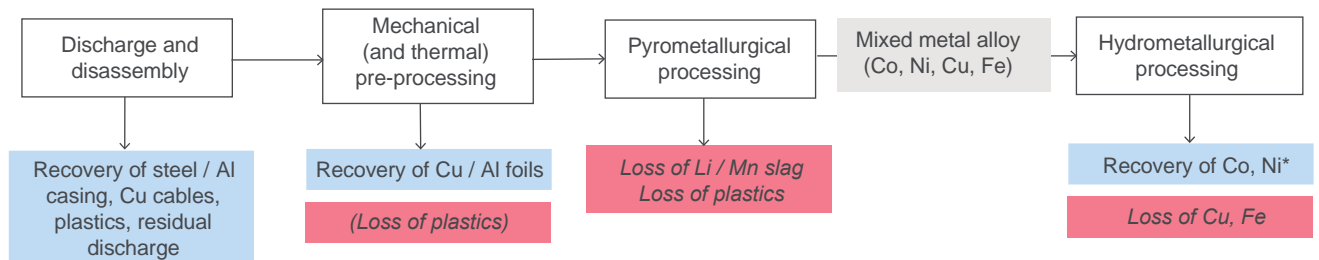
Typical mechanical pre-processing and hydrometallurgical route



Typical pyrometallurgical and hydrometallurgical route



Typical mechanical pre-processing, pyrometallurgical and hydrometallurgical route



*note Li can also be recovered from the slag through the hydrometallurgical process but it is not typically recovered

Figure 2: Overview of EOL LIB recycling pathways and material recovery⁵⁸

Key observations:

- The most established processes are not optimised to recover all materials and are typically focused on recovering cobalt and nickel at a quality suitable for new battery manufacturing. For other major materials (lithium and copper), these processes may be generally characterised as downcycling, and in some cases, lithium is not recovered.
- The ‘other industrial processes’ operate at very large scales and are all characterised as downcycling.
- There are a range of promising technologies that demonstrate that recycling is technically feasible for a broader range of metals. These processes are capable of recovering cobalt, lithium and nickel at a quality suitable for cathode manufacturing, or even as a material stream that is suitable for the direct production of new battery cells. All the emerging processes target the recovery of cobalt and lithium and recycle or downcycle nickel and copper.

⁵⁸ Adapted from Bartosinski, M. (2017) Processing of spent Li-ion batteries: Environmental challenges, ICBR Lisbon September, 2017

Table 6: Summary of LIB recycling processes from Velázquez-Martínez et al.⁵⁹ and IEA⁶⁰

Process name	Feed/Input	Capacity (tonnes/year)	Processing route	Output to battery industry	Output to other industries	Quality of recovered metal
Established LIB recycling processes						
Retriev	LIBs	4500	Mechanical pre-processing / Hydro	metal oxides (incl. CoO)	lithium carbonate (Li ₂ CO ₃), steel, copper, aluminium, cobalt	<i>Recycling</i> – cobalt <i>Downcycling</i> – lithium, nickel, copper
Sumitomo-Sony ('sony process')	LIBs	150	Pyro / Hydro	cobalt (CoO)	cobalt-nickel-iron alloy, copper, aluminium, iron	<i>Recycling</i> – cobalt (processing required) <i>Downcycling</i> – nickel, copper <i>Not recovered</i> – lithium
SungEel HiTech	LIBs	8000	Mechanical pre-processing / Hydro	lithium salts (Li ₂ PO ₄), cobalt (CoO), nickel, manganese	steel, copper, aluminium	<i>Recycling</i> – cobalt, lithium, nickel <i>Downcycling</i> – copper
Recupyl process	LIBs	110	Mechanical pre-processing / Hydro	lithium salts (Li ₂ CO ₃ , LiCO ₂ , Li ₂ PO ₄ , LCO/Co(OH) ₂ /Co)	steel, copper, aluminium, metal oxides (incl. nickel), carbon	<i>Recycling</i> – cobalt, lithium <i>Downcycling</i> – nickel, copper
Umicore process	LIBs (and NiMH bat.)	7000	Pyro / Hydro	cobalt (CoCl ₂), nickel, copper, iron	Slag containing aluminium, silicon, calcium, iron, lithium, manganese, rare earth elements	<i>Recycling</i> – cobalt (ready for LiCoO ₂ synth.), nickel, copper <i>Not recovered</i> – lithium
GEM High-Tech	LIBs	10000	Mechanical pre-processing / Hydro	No data	No data	<i>Recycling</i> – cobalt, nickel ⁶¹
BRUNP	LIBs	25000	Mechanical pre-processing / Hydro	No data	No data	<i>Recycling</i> – cobalt, nickel ⁶²
Akkuser process	LIBS	4000	Mechanical pre-processing	Pre-processing only	cobalt, carbon, copper, iron	<i>Recycling</i> – further processing required through hydromet process

⁵⁹ Velázquez-Martínez, O., Valio, J., Santasalo-Aarnio, A., Reuter, M. and Serna-Guerrero, R., 2019. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries*, 5(4), p.68

⁶⁰ International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>

⁶¹ Information available online here: <http://en.gem.com.cn/>; and <https://lithium.ellenmacarthurfoundation.org/case-studies/avoiding-3-million-tonnes-of-waste>

⁶² Information available online here: https://lithium.iru-miru.com/en/article_detail.php?id=29876; and <https://lithium.argusmedia.com/en/news/1891791-chinas-brunp-to-build-li-ion-cathode-material-plant>

Process name	Feed/Input	Capacity (tonnes/year)	Processing route	Output to battery industry	Output to other industries	Quality of recovered metal
Other industrial processes						
Batrec (originally developed for alkaline/Zn-C batteries)	LIBS	200	Pyro / Hydro	No details	No details	No details
Immetco (batteries / other scrap)		6000	Pyro	Not applicable	cobalt-nickel-iron alloy, other mixed metallic slag	<i>Downcycling</i> – lithium, cobalt, nickel, copper
Glencore		7000	Pyro / Hydro	Not applicable	cobalt-nickel-iron alloy, other mixed metallic slag	<i>Downcycling</i> – lithium, cobalt, nickel, copper
Emerging LIB recycling processes						
Accurec (developed for NiCd)	LIBs	(batch)	Mechanical pre-processing / Pyro / Hydro	lithium carbonate (Li ₂ CO ₃), cobalt-nickel-manganese alloy	mixed metallic slag	<i>Recycling</i> – Cobalt (elemental), lithium <i>Downcycling</i> – nickel, copper
Battery Resources “closed Loop”	LIBs LiNi _x Mn _y CO ₂ O ₂ cathode chemistry	Commercialisation phase	Mechanical pre-processing / Pyro / Hydro	lithium carbonate (Li ₂ CO ₃), NMC(OH) ₂	ferrous metals	<i>Recycling</i> – Cobalt (ready for cathode synth.), lithium, nickel <i>Downcycling</i> – copper
Lthorec	LIB modules (target traction applications)	No data	Mechanical pre-processing / Pyro / Hydro	lithium carbonate (Li ₂ CO ₃), mixed metal oxides (incl. cobalt oxide)	aluminium, copper, plastic	<i>Recycling</i> – lithium, cobalt (ready for cathode synth.) <i>Downcycling</i> – nickel, copper
OnTo or EcoBat	LIB and components	No data	Mechanical pre-processing / Pyro / Hydro	refurbished cathode powder	iron, aluminium, copper	<i>Recycling</i> – cobalt, lithium, nickel <i>Downcycling</i> – copper
Aalto University	Lab-scale process	No data	Mechanical pre-processing / Pyro / Hydro	CoC ₂ O ₄ , aluminium, lithium and nickel in solution	No details	<i>Recycling</i> – cobalt, lithium, nickel (requires further processing) <i>Downcycling</i> – copper

Table 7 provides a summary of the current recovery pathways and recycling rates, as well as potential that we used to quantify potential reductions in primary demand. The current recovery rates are an estimation of what is currently happening in the market, based on the share of processing capacity (considered in this study in Table 6) that recycles metals at a quality suitable for battery manufacturing. The potential recycling rates are based on input from stakeholder interviews. These rates are used for the quantitative projections in Part 2.

Table 7: Summary of recovery pathways and recycling rates for lithium-ion batteries

	Typical recovery pathways from LIB	Potential recovery pathways from LIB	Estimated current recycling rates from LIB	Potential future recycling rates from LIB
Cobalt	Typically recycled (Retriev, Sumitomo, SungEel, Recupyl GEM High-Tech, BRUMP and Umicore process), sometimes downcycled	Plan to be recycled in major emerging processes	80% (assumed ~ 88% of recycling capacity recovers 90% of cobalt)	95%
lithium	Typically downcycled or not recovered (recycled only in SungEel and Recupyl process)	Plan to be recycled in major emerging processes	12% (assumed ~ 13% of recycling capacity recovers 90% of lithium)	95%
Nickel	Sometimes recycled (SungEel, GEM High-Tech, BRUMP and Umicore process) or downcycled	Plan to be recycled or downcycled in major emerging processes	73% (assumed ~ 81% of recycling capacity recovers 90% of nickel)	95%
Copper	Typically downcycled (recycled only in Umicore process) [Note additional recovery may happen in pre-processing]	Plan to be recycled or downcycled in major emerging processes	10% (assumed ~ 11% of recycling capacity recovers 90% of copper)	95%

Potential to use recycled metals in lithium-ion battery manufacturing

Overview of the LIB supply chain

The production process of LIB has several steps, beginning with mining or secondary metal supply, metal processing, production of battery chemicals such as cathode active material (CAM), cell manufacturing and battery assembly. The metals of focus in this study are used in the following ways:

- Cobalt, lithium and nickel are used in the cathode of LIB. Typically a precursor producer (mostly located in China, Japan and South Korea, with a small number in Europe and the US) will source these metals to produce a cathode active material (CAM). For EV batteries, cobalt and nickel are used as sulphates and lithium as a hydroxide. The CAM is then sold to cell manufacturers for production of the cathode and battery cells.
- Copper is used as a foil and would typically be sourced by the cell manufacturer.

LIB battery manufacturing has high specifications for pure and high-quality battery grade materials, which may limit the use of secondary materials.

Use of metals in LIB cathodes

Cobalt sulphate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) is the precursor material used for the manufacturing of Nickel-Cobalt-Manganese (NCM) and Nickel-Cobalt-Aluminium (NCA) LIBs, which are projected to be the dominant battery chemistries for EVs. Cobalt oxide is the precursor material for lithium-Cobalt-Oxide (LCO) LIBs which are typically used in consumer electronics.⁶³

Cobalt sulphate is produced by various Chinese producers, as well as Glencore, Umicore, Freeport Cobalt in Finland and Sumitomo in Japan.

Lithium hydroxide ($\text{LiOH} \cdot \text{H}_2\text{O}$) is the precursor material used for the manufacturing of NCM chemistries. lithium hydroxide can be produced from lithium carbonate from brine processing or from mineral conversion from spodumene. Lithium hydroxide has predominantly come from the conversion of carbonates, but since 2016 several mineral conversion operations have expanded, and approximately 40% of lithium hydroxide was produced from spodumene in 2018.

Three companies (Albemarle, Livent and Ganfeng lithium) produced more than 60% of battery and technical grade lithium hydroxide in 2018.

Nickel sulphate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$) is the precursor raw material used in the manufacturing of the cathode for LIB, which is produced from high-purity nickel (Class I nickel) or other intermediate products.⁶⁴ The majority of nickel sulphate is produced in Japan and China, as well as at Nornickel's plant in Finland, Umicore's plant in Belgium, and small producers in Taiwan, India, Germany and the US.

It is estimated that 20-25% of nickel sulphate is from recycled sources in 2019/2020, although this percentage is projected to decrease as a share of total nickel supply with new and expanded nickel refining projects.⁶⁵ It is not known what percentage is battery grade.

⁶³ https://lithium.cleanteq.com/wp-content/uploads/2016/12/9772_Clean-Teq-LITHIUM-ION-BATTERIES_17-1-17.pdf

⁶⁴ Roskill., 2019. lithium-ion Batteries: Outlook to 2028. 3rd ed. London: Roskill Information Services – cited in Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

⁶⁵ Roskill., 2019. lithium-ion Batteries: Outlook to 2028. 3rd ed. London: Roskill Information Services – cited in Talbot., P. and Watts., J., 2020. Li-ion battery cathode manufacture in Australia: A Scene Setting Project. Available at: <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

Current use of recycled content:

It is likely that only a small portion of cobalt and nickel supply in current manufacturing is coming from recycled sources, and that there is very little, or no lithium being used. Recycled content that does enter the manufacturing process for these three metals is most likely to come from EOL LIB, however there are small volumes of metals available from EOL LIB compared to the current demand. There are already some examples of recycling companies working directly with the battery manufacturing supply chain, for example SungEel High Tech in South Korea, which is owned by Samsung.

It is unlikely that any recycled sources of these metals are coming from other sources. For cobalt, scrap is likely to be recycled into the same end-use (e.g. superalloys) and cobalt from LIB from electronic items is likely to be used again for electronics, as it is used in a different form to that in EV batteries. Similarly, nickel used in stainless steel or alloys is typically recycled back into the same end-markets. For lithium, this is because of very low recycling rates in other applications, many of which are technically very difficult to recover.

For copper, it is likely that a more significant portion of supply in manufacturing could come from recycled sources. This metal is most likely to come from other end-markets as secondary copper is processed with primary copper for the smelting and refining stages (likewise aluminium).

Future use of recycled content:

In future, EOL EV LIB is likely to be the major source for secondary metals for cobalt, lithium and nickel. Even though it is technically possible to recover these metals from other sources, the other major end markets are likely to continue to increase in demand. Recovering these metals from used LIB back into precursor materials is likely to be the most economic route compared to returning them to pure metals from other sources.

Stakeholders interviewed for this study commented that the market is likely to see an initial decline in the share of recycled sources for these metals while the demand for EVs increases and before the supply of EOL EV LIB becomes significant.

Copper is likely to come from general copper recycling routes. Copper could in theory come from recycled LIB, but economically it is unlikely to make sense as it would mean more processing for a recycler for a similar price. Copper is also not a priority in EOL LIB recovery. Most recycled copper is likely to be recovered through the general copper scrap route, which may include EOL LIB in countries with primary copper smelting.

Table 8: Summary across metals

Potential for recycled content in LIB manufacturing

	Use of secondary sources from other markets – current	Use of secondary sources from other markets – potential	Use of secondary sources from LIB – current	Use of secondary sources from LIB – potential
Cobalt	Unlikely because of small volumes compared to current cobalt demand (even though cobalt scrap is often recycled, unlikely to be used for LIB). Cobalt typically recycled (from electronics LIB) to cobalt-tetra-oxide which goes to LCO batteries (electronics).	Technologically possible but unlikely.	Some may be used from recycled sources as cobalt is a priority in recovery. However there are small volumes compared to current demand and the % is projected to decline. Umicore estimate 9.2% of 2019 cobalt supply is from secondary sources. ⁶⁶	Most likely secondary source is EOL EV LIB. Processing the used EV LIB mixed metal dust back into precursor materials is more economical than back to a pure metal, some companies are already doing this and selling to the battery industry.
Lithium	Very unlikely because of small volumes compared to current lithium demand, poor recycling rates (<1%) and difficulty recovering in most applications.	Not possible in most applications.	Unlikely to be coming from recycled sources because lithium is not always recovered and there are small volumes compared to current demand.	Most likely secondary source is EOL EV LIB. Processing the used EV LIB back into precursor materials is more economical than back to a pure metal, most emerging LIB recycling processes are targeting lithium recovery.
Nickel	Unlikely because stainless steels and alloys are majority of the market and are typically recycled into the same applications.	Technologically possible but unlikely. Stainless steel and alloys will continue to be important markets. Sources would need to be a pure nickel metal.	Some may be used from recycled sources, although there is lower market demand for secondary nickel compared to cobalt. However, there are small volumes compared to current demand and the % is projected to decline.	Most likely secondary source is EOL EV LIB. Processing the used EV LIB back into precursor materials is more economical than back to a pure metal, some companies are already doing this and selling to the battery industry.
Copper	Likely that a portion comes from other end-markets as secondary copper is processed with primary for the smelting and refining stages (likewise aluminium).	Likely that a portion will come from other end-markets in future, but limited by the fact that most in-use copper is in applications with long lifetimes.	Some may be used from recycled sources but this is likely to be through the general copper scrap route as not a priority in recovery from LIB. One recycler in Australia noted that copper was downcycled with aluminium to brass.	Could in theory come from recycled LIB but economically unlikely to make sense, would be more processing for recycler to sell at similar price. Likely to be through the general copper scrap route.

⁶⁶ Umicore (2019) Due Diligence Compliance Report Cobalt Procurement 2019, <https://lithium.umicore.com/en/about/sustainability/due-diligence-compliance-report-cobalt-procurement>

Potential for reducing demand for primary materials in lithium-ion batteries and electric vehicles

A number of strategies to may be employed to effectively reduce demand for new batteries in EV and energy storage applications, in line with circular economy principles,⁶⁷ The key options considered here are the extension of battery life, including through refurbishment and reuse in second life applications, and the replacement of private ownership with shared vehicle ownership models. A summary of these strategies is presented in Table 9.

Table 9: Potential for reducing demand for lithium-ion batteries

	Current situation	Potential	Limitations
Extending battery lifetimes	Current lifetimes estimated between 8 years (current warranties) and 15 years. ⁶⁸	Several OEMs are working on developing batteries with longer lifetimes, which could reach approximately 20 years. ⁶⁹	Consumers are more likely to upgrade vehicles before end-of-battery life.
Reuse	Reuse schemes allow batteries to have a 'second-life' in a new application once they are no longer considered suitable for use in EVs. Some applications in operation, e.g. EOL EVs are being reused for stationary storage, refurbishment for use in other types of vehicles and some OEMs are looking into EV-to-EV applications.	The most likely market is the use of EOL EVs in grid storage applications, with potential lifetimes of 12 years (second life). ⁷⁰	The variation between battery design and chemistries limits refurbishment and reuse unless initiated by the OEM.
Shifts away from private car ownership	Car sharing schemes have the potential to reduce the number of privately-owned cars, but there are very few applications in operation.	Vehicles used in sharing schemes may be used more intensively which could shorten battery life, however the management of vehicles by scheme may allow for best practice battery management slowing the rate of battery degradation.	There is limited evidence to suggest that car sharing schemes have resulted in a significant reduction in car ownership and/or influenced battery demand considering current examples. Consumer preferences and a lack of policy support remain major limitations to further expansion.
Improved public and bike transit	Access to efficient, convenient, inexpensive and adequately connected public and bike transit options.	Well-connected and incentivised electric buses, trains and other forms of collective transport and improved provision of bike infrastructure have the potential to reduce demand for private cars.	Policy actively promoting public and bike transit infrastructure

Extending battery life

The average lifespan of an EV battery depends on the generation and fabrication process (newer batteries have improved technology), how the battery is charged, the frequency of charging, climatic conditions and how far it

⁶⁷ Ellen-MacArthur-Foundation. (2020). What is the Circular Economy? Ellen Macarthur Foundation <https://lithium.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy>

⁶⁸ Davis, S. C., & Boundy, R. G. (2020). Transportation Energy Data Book: Edition 38.1. Oak Ridge: Oak Ridge National Laboratory. Available online: https://tedb.ornl.gov/wp-content/uploads/2020/02/TEDB_Ed_38.pdf#page=89

⁶⁹ Engadget (2018) 'Tesla batteries will live longer than expected, survey finds'. Available online: <https://lithium.engadget.com/2018-04-16-tesla-battery-packs-live-longer.html>

⁷⁰ Casals, L. C., García, B. A., & Canal, C. (2019). Second life batteries lifespan: Rest of useful life and environmental analysis. Journal of environmental management, 232, 354-363. Available online: <https://lithium.sciencedirect.com/science/article/pii/S0301479718313124>

is driven.⁷¹ Battery lifespan degradation may be hastened by: exposure to high temperatures, operating at high and low states of charge, exposure to high electric current, and high usage (number of energy cycles). While it is too early to definitively predict the life of the current generation of EV batteries, some reasonable estimations can be made. Most battery warranties are around 8 years or 100,000 miles (~161,000 km). While some earlier hybrid EV models, such as the Toyota Prius may be expected to only reach 100,000 miles⁷², it is anticipated that most batteries produced more recently will outlast this conservative warranty lifetime by a significant margin. Research using owner surveys found that most Tesla vehicles will likely have 90% capacity after 185,000 miles (300,000 km), and 80% capacity after 500,000 miles (800,000 km).⁷³ Based on driving statistics for the United States, the average driver logs approximately 13,476 miles per year⁷⁴, meaning the battery may last over 20 years.

Given these expected battery lifetimes it has been predicted that batteries will often outlast the service life of the vehicle, which is estimated to be around 15 years when car upgrades and use-related damage are taken into account.⁷⁵ Some studies have consequently taken 15 years as a reasonable duration estimate for a battery's first life, which was confirmed in stakeholder consultation. In the United States, approximately 67% of all vehicles have been removed from service after 15 years.⁷⁶ Several OEMs have reported that they are working on developing batteries with longer lifetimes. The managing director of Renault-Nissan Energy Services has stated he expects the Nissan Leaf batteries could last for 22 years of driving. Tesla has also reported that they are close to developing new battery chemistries to make EV battery cells last 1 million miles, which could make second life options more viable.⁷⁷

Battery refurbishment and reuse

One 2015 study claims that, on average, a battery is likely to have around 70% of its initial capacity if retired at 15 years, and that 80% of batteries will be eligible for repurposing after that time.⁷⁸ As noted above, battery degradation rates are dependent on a number of factors that may vary with different applications.

Assessing second life options

Accurate, high-fidelity battery life models and experimental data for battery degradation are still not widely available, meaning that a number of assumptions have to be made about probable first and second battery lifetimes under different conditions. However, a number of insights can be gleaned from current research initiatives about the most viable ways of reducing demand for batteries via battery use practices, sharing business models for EVs, and second life applications. Research suggests that exchangeable refurbished batteries for EVs are nearing commercialisation for some manufacturers, however this is only possible within a controlled, take back system at present.⁷⁹ However, applications for low-power vehicles such as forklifts, golf and airport buggies and city ferries which do not require batteries to be refurbished may be a growing market in future if costs associated with testing, disassembly and refitting into new vehicles are able to be kept low.⁸⁰

⁷¹ McKinsey & Company (2019) Second-life EV batteries: The newest value pool in energy storage, <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage>

⁷² EnelX (2020) How Long Do Electric Car Batteries Last? Available online: <https://evcharging.enelx.com/news/blog/512-electric-car-battery-life>

⁷³ Engadget (2018) 'Tesla batteries will live longer than expected, survey finds'. Available online: <https://lithium.engadget.com/2018-04-16-tesla-battery-packs-live-longer.html>

⁷⁴ Federal Highway Administration (2018) 'Average Annual Miles per Driver by Age Group'. Available online: <https://lithium.fhwa.dot.gov/ohim/onh00/bar8.htm>

⁷⁵ Davis, S. C., & Boundy, R. G. (2020). Transportation Energy Data Book: Edition 38.1. Oak Ridge: Oak Ridge National Laboratory. Available online: https://tedb.ornl.gov/wp-content/uploads/2020/02/TEDB_Ed_38.pdf#page=89

⁷⁶ Ibid

⁷⁷ Rae, Alex (2020) GM vs Tesla for the million-mile battery. Practical motoring. Available online at: <https://practicalmotoring.com.au/car-news/gm-vs-tesla-for-the-million-mile-battery/>

⁷⁸ Neubauer, J., Smith, K., Wood, E., & Pesaran, A. (2015). *Identifying and overcoming critical barriers to widespread second use of PEV batteries* (No. NREL/TP-5400-63332). National Renewable Energy Lab.(NREL), Golden, CO (United States).

⁷⁹ CleanTechnica (2018) Nissan Begins Offering Remanufactured Batteries For LEAF. Available online: <https://cleantechnica.com/2018/05/15/nissan-begins-offering-remanufactured-batteries-for-leaf/>

⁸⁰ Group Renault (2019) 'The circular economy applied to electric vehicles.' Available online: <https://easyelectriclelife.groupe.renault.com/en/outlook/the-circular-economy-applied-to-electric-vehicles/>

Enabling factors for second life applications

There are currently a number of inhibiting factors that may need to be addressed to enable effective battery refurbishment and reuse for most second life applications. Key factors include:

1. **Design and standardisation** – At present, the structure of batteries is determined by the manufacturer based on application requirements. For example, by 2025 there will be around 250 new EV models on the market with batteries from more than 15 different manufacturers with very limited or no adherence to design standards.⁸¹ Integrated construction of battery packs in addition to proprietary battery management software further inhibits component replacement, testing and reuse.
2. **Scaling processing** – Currently it is estimated that there is a 30 – 70% cost advantage for second life batteries over new ones for energy storage applications. However, it is anticipated this may drop to around 25% by 2040 as new batteries become cheaper. To remain competitive, scaling up processing to reduce costs will likely be required.⁸² On the other hand, because the market for EVs is expected to be much larger than the market for stationary energy, the number of available second life batteries will increase relative to demand.
3. **Standards** – To create customer certainty and ensure viability, stricter standards regarding quality, safety, and performance are required in most markets. A regulatory body that is able to review and refine battery standards and report regularly on costs and operating benchmarks would be beneficial. It may also decrease potential resistance from utilities requiring high reliability.⁸³
4. **Testing** – More efficient and robust means of testing battery systems, particularly for storage applications, is required to determine how many cells have failed.⁸⁴
5. **Battery management systems** – There are repurposing challenges due to control of battery management systems.⁸⁵
6. **Regulatory inhibitors** – Significant barriers currently exist regarding the collection and transport of batteries intended for reuse across jurisdictions. One report on battery second use from Navigant Research identifies limitations with shipping EOL batteries for reuse, as all batteries removed from vehicles in the United States and Europe are presently classified as hazardous waste.⁸⁶ Coordinated policy approaches to incentivise the establishment of take-back and collection systems may help remove some of these regulatory barriers. For example, further development of Extended Producer Responsibility schemes has the potential to drive changes across these key enabling areas.

While vehicle to vehicle second life battery applications are still uncommon, some estimates suggest that future EV numbers could provide an EOL energy storage application market with an global value of around \$30 billion

⁸¹ McKinsey & Company (2019) Second-life EV batteries: The newest value pool in energy storage, <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage>

⁸² Ibid

⁸³ Neubauer, J., Smith, K., Wood, E., & Pesaran, A. (2015). *Identifying and overcoming critical barriers to widespread second use of PEV batteries* (No. NREL/TP-5400-63332). National Renewable Energy Lab.(NREL), Golden, CO (United States).

⁸⁴ Florin, N., Wakefield-Rann, R., Dominish, E. Dwyer, S., Gertsakis, J. And Hartford, N. (2020) Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium

⁸⁵ Neubauer, J., Smith, K., Wood, E., & Pesaran, A. (2015). *Identifying and overcoming critical barriers to widespread second use of PEV batteries* (No. NREL/TP-5400-63332). National Renewable Energy Lab.(NREL), Golden, CO (United States).

⁸⁶ Jaffe, S.; Adamson, K. (2014) "Second-Life Batteries: From PEVs to Stationary Applications." RB-SLB-14. Navigant Research. Cited in: Neubauer, J., Smith, K., Wood, E., & Pesaran, A. (2015). *Identifying and overcoming critical barriers to widespread second use of PEV batteries* (No. NREL/TP-5400-63332). National Renewable Energy Lab.(NREL), Golden, CO (United States).

by 2030.⁸⁷ One report⁸⁸ has proposed that reuse can add most value in markets for stationary energy-storage that need less-frequent battery cycling (i.e. 100 to 300 cycles/year), because the power capability may be degraded by a much larger factor than the energy density of used cells. On this basis, they propose that the most suitable applications are likely to involve low frequency cycling, such as:

1. reserve energy capacity for maintaining power reliability of utility providers at low cost,
2. deferring distribution and transmission investments, and
3. using power-arbitrage opportunities by storing power for use during scarcity and providing greater grid flexibility.

Battery leasing systems may help to increase second-life applications.⁸⁹ In these business models, a customer purchases the vehicle, but the manufacturer retains ownership of the battery, enabling them to monitor and take back the battery when it will still offer value for second life applications. This approach may also incentivise manufacturers to use battery management systems and other tools to ensure optimal charging and use practices to prolong battery life. This is more likely to be attractive to manufacturers as second-life markets become more stable and the residual value of batteries becomes more apparent.⁹⁰

Shifts away from private car ownership

Car sharing schemes employing EVs could reduce the number of privately-owned cars on the roads under the right contextual conditions.⁹¹ Studies on car sharing in general have proposed that each car shared has the potential to reduce the need for 6–23 private cars in North America, 4–10 in Europe, and 7–10 in Australia.⁹² However, given the difficulty of controlling all relevant variables on car use, even within a given context, direct comparisons are limited. Direct comparisons in terms of the number of EVs, average LIB battery lifetimes or relative degradation rates between private and shared vehicles could not be found.

Research has shown that battery life under both private and share use scenarios differ greatly depending on charging practices, location temperature, and distance travelled. While shared vehicles may be subject to more frequent use, which could reduce battery life (although not necessarily), the management of vehicles by a single scheme owner may allow for best practice battery management to be enacted more effectively than under private ownership.⁹³ These findings have implications for the longevity of all EV batteries. Battery lifetimes differ according to the sharing models adopted. For example, one study found that a vehicle in a large sharing company needed 78% of the time to reach battery EOL than one shared in a co-housing model.⁹⁴

⁸⁷ McKinsey & Company (2019) Breathing new life into used electric vehicle batteries <https://lithium.mckinsey.com/business-functions/sustainability/our-insights/sustainability-blog/breathing-new-life-into-used-electric-vehicle-batteries>

⁸⁸ McKinsey & Company (2019) Second-life EV batteries: The newest value pool in energy storage, <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage>

⁸⁹ McKinsey & Company (2019) Second-life EV batteries: The newest value pool in energy storage, <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage>

⁹⁰ McKinsey & Company (2019) Second-life EV batteries: The newest value pool in energy storage, <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage>

⁹¹ Rigole, P. J. (2014) Study of a shared autonomous vehicles based mobility solution in Stockholm. Master of Science Thesis, Stockholm Available online: <https://lithium.diva-portal.org/smash/get/diva2:746893/FULLTEXT01.pdf>:

Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies*, 40, 1-13. Available online:

https://lithium.sciencedirect.com/science/article/pii/S0968090X13002581?casa_token=vvkL-wFnIUAAAAA:hm4xM7ruggXJrCRaumSrnyqnY9p6_93i9IELu4THtnw-bLGgRQ-yDmbkaac5Gii13ewA3YR8fxh

⁹² Shaheen, S. A., & Cohen, A. P. (2007). Growth in Worldwide Carsharing: An International Comparison. *Transportation Research Record*, 1992(1), 81–89. <https://doi.org/10.3141/1992-10>; & Rydén, C., and E. Morin. Mobility Services for Urban Sustainability: Environmental Assessment. Report WP 6. Trivector Traffic AB, Stockholm, Sweden, January 2005. 213.170.188.3/moses/Downloads/reports/del_6.pdf.

⁹³ Semajski, I., & Gautama, S. (2016). Forecasting the state of health of electric vehicle batteries to evaluate the viability of car sharing practices. *Energies*, 9(12), 1025.

⁹⁴ Semajski, I., & Gautama, S. (2016). Forecasting the state of health of electric vehicle batteries to evaluate the viability of car sharing practices. *Energies*, 9(12), 1025.

Table 10: Potential pathways for refurbishment and reuse of EV batteries

Pathway	Key applications	Market-readiness	Second Life
EV to EV	Processes are in operation that involve battery disassembly and replacement of low-capacity modules for refurbishment and reuse in EVs.	Some applications in operation or in development but not widely used. E.g. Nissan can refurbish 24 kWh batteries from the first gen Nissan LEAF that have lost 20% or more of their capacity. ⁹⁵ In future Nissan plans to refurbish 30 and 40 kWh battery packs and expand their capacity to be able to remanufacture 2,250 batteries a year. ⁹⁶	Not stated.
EV to other vehicles	EV batteries containing modules with ~70% capacity at EOL can be used for other vehicle applications that do not require the power of standard EVs, for example forklifts, golf and airport carts, and ferries.	Some applications in operation or in development but not widely used. E.g. second life Renault EV batteries are being used by Carwatts in airport baggage carts ⁹⁷ and Black Swans to power the first electric river boat in Paris. ⁹⁸	Not stated.
EV to fast charge stations	Second life EV batteries can be used to provide power to support fast charging stations, rather than increasing the power supply installation.	Market ready.	Almost 30 years. ⁹⁹
EV to large scale energy storage	Second life EV batteries can be used for large scale stationary storage applications, storing energy in periods of peak production and releasing energy to the grid during periods of peak demand, and providing power support. This may defer the need for new transmission infrastructure.	Currently in operation, e.g. BMW have created a battery storage farm from used EV batteries to at their Leipzig factory ¹⁰⁰	Approx 12 years. ¹⁰¹
EV to small scale storage	Second life EV batteries can be used in rooftop PV systems with a capacity for storing around 6 kWh. These batteries can also be connected to the grid to provide grid stability services.	Current examples include used Nissan LEAF batteries home photovoltaic systems in the UK and camping trailers. ¹⁰² In Japan, Toyota are planning second life EV batteries to provide storage at 7-Eleven stores. ¹⁰³	Approx 12 years, or 6 if providing grid stability services.

⁹⁵ CleanTechnica (2018) Nissan Begins Offering Remanufactured Batteries For LEAF. Available online: <https://cleantechnica.com/2018/05/15/nissan-begins-offering-remanufactured-batteries-for-leaf/>

⁹⁶ ReMaTec (2018) Turning over a new LEAF. Available online: <https://lithium.rematec.com/news/turning-over-a-new-leaf/>

⁹⁷ Group Renault (2019) 'The circular economy applied to electric vehicles.' Available online: <https://easyelectriclife.groupe.renault.com/en/outlook/the-circular-economy-applied-to-electric-vehicles/>

⁹⁸ Group Renault (2019) 'The first all-electric boat on the seine'. Available online: <https://easyelectriclife.groupe.renault.com/en/expert-view/first-all-electric-boat-renault-seine-alliance/>

⁹⁹ Casals, L. C., García, B. A., & Canal, C. (2019). Second life batteries lifespan: Rest of useful life and environmental analysis. *Journal of environmental management*, 232, 354-363. Available online: <https://lithium.sciencedirect.com/science/article/pii/S0301479718313124>

¹⁰⁰ BMW (2017) BMW Group underlines leading role in electro-mobility. Available online: <https://lithium.press.bmwgroup.com/global/article/detail/T0275547EN/bmw-group-underlines-leading-role-in-electro-mobility?language=en>

¹⁰¹ Casals, L. C., García, B. A., & Canal, C. (2019). Second life batteries lifespan: Rest of useful life and environmental analysis. *Journal of environmental management*, 232, 354-363.

¹⁰² Nissan (2019) Nissan x Opus concept camper uses second-life ev batteries to power 'off-grid' adventures. Available online: <https://lithium.nissan.com.au/about-nissan/news-and-events/news/2019/Feb/nissan-x-opus-concept-camper-uses-second-life-ev-batteries-to-power-off-grid-adventures.html>

¹⁰³ Australian Energy Council (2019) 'Storage: Retirement home for old EV batteries?' Available online: <https://lithium.energycouncil.com.au/analysis/storage-retirement-home-for-old-ev-batteries/>

Part 2: Quantifying potential reductions in primary demand through recycling

This chapter presents projections for the demand for cobalt, lithium, nickel and copper for EV LIBs in a future renewable energy system. The aim of this analysis is to explore how primary demand could be minimised through changes in recycling. We consider how recycled content from the general end-market or from EOL EV LIBs might impact primary demand, and how this may change over time.

Key assumptions and approach

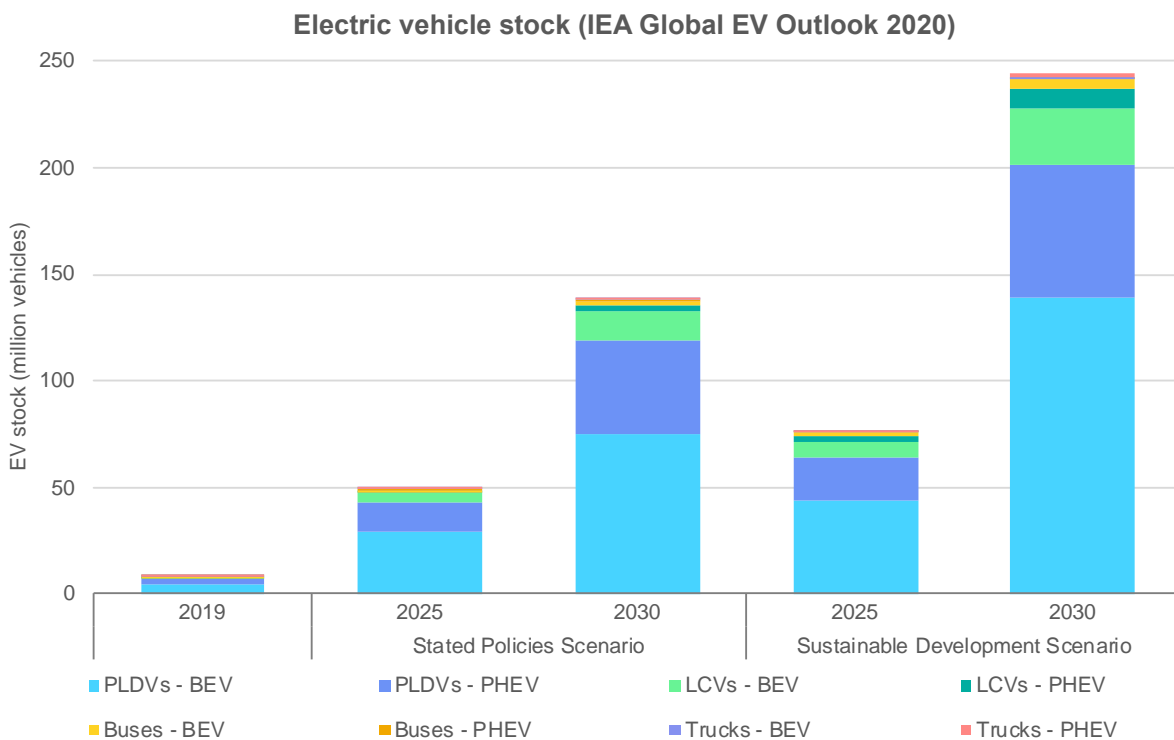
EV demand scenario

The future demand for metals has been modelled against the International Energy Agency's (IEA) Global EV Outlook 2020.¹⁰⁴ The outlook presents two scenarios for EV demand:

- The Stated Policies Scenario, which aims to project demand based on existing and announced policy measures put in place by governments, as well as the expected effects of targets and plans announced by governments and industry; and
- The Sustainable Development Scenario, which aims to meet global climate goals in line with the Paris Agreement, limiting global temperature rise to below 1.7-1.8 degrees Celsius, as well as ensure universal energy access by 2030 and bring a sharp reduction in emissions of air pollutants. This scenario incorporates the aims of the EV30@30 Campaign, a target from eleven countries to achieve a 30% market share for EVs by 2030. This scenario also accounts for a reduction in number and distance of trips by car and a larger share of travel on public and active transport.

Both scenarios include projections of battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), across four types of vehicles: passenger light-duty vehicles (PLDVs), light-commercial vehicles (LCVs), buses and trucks (see Figure 3).

Figure 3: Electric vehicle stock (IEA Global EV Outlook 2020)



¹⁰⁴ International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>

Modelling approach

The IEA scenarios provide the following data:

- Vehicle stock (million vehicles) for 2025 and 2030, for PLVDs, LCVs, buses and trucks
- Vehicle sales (million vehicles/year) for 2025 and 2030
- Battery capacity additions (GWh/year)

From this data, the average battery size per vehicle was calculated over the time period. The projection of vehicle stock was extended to 2040 following the projected trendline, so that the timeframe of the analysis could better explore the impact of recycling on metal demand for batteries considering the lag in availability of EOL EV LIBs. The following projections were calculated for the four metals:

- Total metal demand (using an assumed metal intensity of tonnes per GWh of battery capacity)
- Primary metal reduction from using recycled content from general end-markets
- Primary metal reduction from recycling of EOL EV LIB at estimated current recovery rates, assuming that recycling continues at current recovery rates and the recycled content is used in new LIB manufacturing
- Primary metal reduction from improved recovery rates from the recycling of EOL EV LIB, assuming that the recycled content is used in new LIB manufacturing

The aim of this approach is to explore how the use of recycled content from general end-markets and from recycling of EOL EV LIB could impact on total demand.

Key assumptions

- Metal intensity: Current metals intensity is based on an assumed market share of a range of LIB technologies: NMC (60%), LMO (20%), NCA (15%), and LFP (5%).¹⁰⁵ For simplicity we assume the metal intensity remains the same across the time period.
- Recycled content: Assumptions are informed by literature review and stakeholder interview data as summarised in Table 8. We note that estimates for recycled content used in EV LIB are highly uncertain, however, we have aimed to use a number most likely for the battery industry. For cobalt and nickel, the share is based on Umicore's current share of recycled content as a proxy for the industry more generally, and for lithium and copper we assume the recycled content in batteries is in line with global recycled content rates.
- Recovery rates: Assumptions are based on a survey of commercial LIB recycling processes and stakeholder interview data as discussed in Table 7. We note that when computing the recovery from recycling we assumed collection rate for EV LIBs of 100%.
- Lifetime: We have used an assumed lifetime of 10 years per battery, based on the discussion of lifetimes in Part 1 and stakeholder inputs.
- Battery size: The average battery size is calculated as an average across the vehicle types. The battery size increases over time, from 55 kWh per vehicle in 2019, to approximately 60 kWh in 2030.

Table 11: Key assumptions

	Metal intensity [tonnes per GWh of battery capacity]	Recycled content from general end-markets	Current recovery rates from recycling	Improved recovery rates from recycling
Cobalt	124 t/GWh	~ 9%	80%	95%
lithium	113 t/GWh	0%	13%	95%
Nickel	415 t/GWh	~ 9%	73%	95%

¹⁰⁵ Values from: Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013

Copper	220 t/GWh	~ 33%	10%	95%
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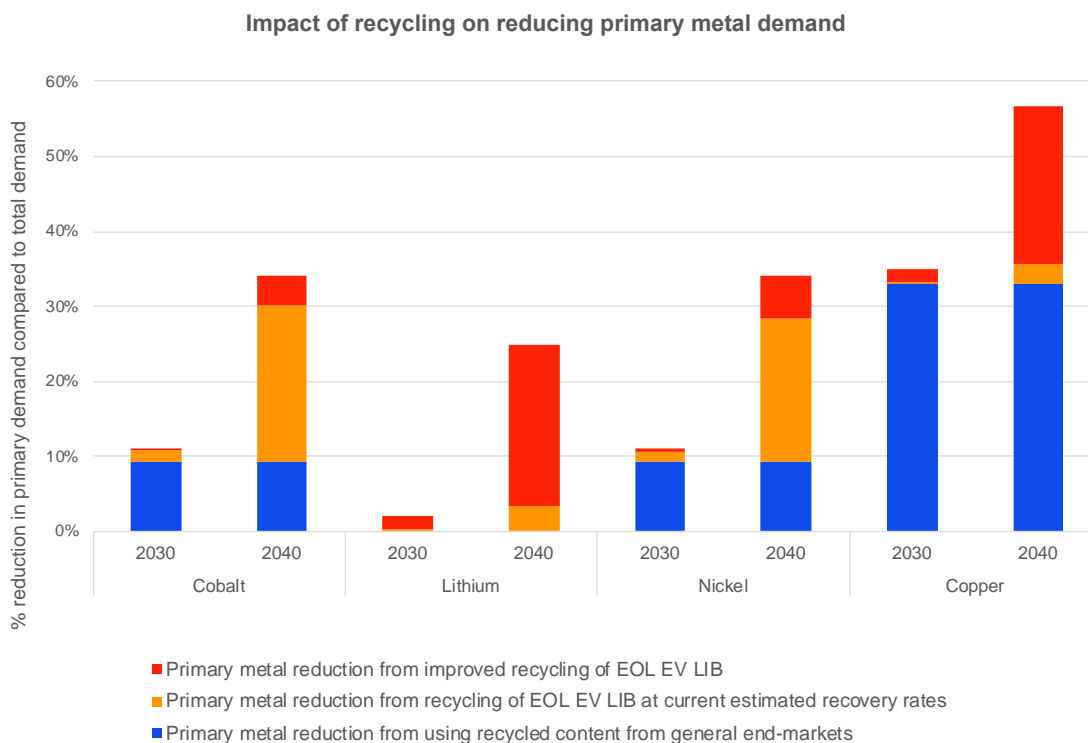
Key findings

The below results are presented for the IEA Sustainable Development Scenario. Figure 4 provides an overview of the impact of recycling on reducing primary metal demand. The chart shows the percentage reduction in demand compared to total metal demand in 2030 and 2040, and the contribution of recycled content from general end-markets [blue], the recycling of EOL EV LIB (assuming that it continues at current recovery rates and the recycled content is used in new LIB manufacturing) [orange] and the additional demand reduction from improving the recovery rates from recycling [red]. Figures 5 to 8 show the demand reduction over time for the four metals.

The key findings include:

- Recycling has the potential to reduce primary demand by between approximately 25% and 55% of total demand in 2040 and can significantly reduce the demand for new mining.
- For cobalt and nickel, the majority of the reduction in primary demand comes from the use of recycled metals from EOL EV LIB at current recovery rates, which are already relatively high. This highlights the importance of maintaining the current high recovery rates of cobalt and nickel from EV LIB recycling as the number of batteries reaching EOL grows, and continuing to improve recovery efficiency, including collection channels for batteries at EOL.
- For lithium, almost all of the reduction in primary demand is expected from the use of recycled metals from EOL EV LIB assuming improved recovery rates. This is because current recovery rates are low, and lithium is very rarely recovered from other end-markets and is unlikely to be in future. This highlights the importance of improving recovery rates of lithium in LIB recycling which has previously not been a focus for most recyclers.
- For copper, the use of recycled content from general end-markets has the most impact on reducing primary demand, followed by the use of recycled metals from EOL EV LIB at an improved recovery rate. This highlights the importance of improving the collection of EOL products that contain copper but have low rates of recycling (such as consumer electrical and electronics) and improving recovery rates in LIB recycling.

Figure 4: Impact of recycling on reducing primary metal demand



Comparison with other demand reduction strategies

In order to compare the impact of recycling to other demand reduction strategies, the equivalent number of battery sales was calculated based on the estimated volume of metal avoided from improving recovery rates compared to current rates.

Improving recycling rates would lead to the equivalent of between 8.5 million (for cobalt) and 45.5 million (for lithium) avoided battery sales out of a total of more than 200 million estimated sales in 2040, equivalent to 4% or 22% of total battery sales respectively. This additional reduction in demand is not insignificant and we note that the current rate of recycling assumed for cobalt is relatively high (80%). However, this does highlight the importance of also pursuing demand reduction strategies of battery reuse and shifts away from private car ownership alongside recycling.

Table 12: Equivalent number of vehicle sales avoided

	Year	Projected number of new EV battery sales	EV battery sales avoided equivalent to primary metal reduction from improved recovery rates (compared to current rates)	Percentage of new EV battery sales avoided
Cobalt	2030	52,500,000	1,000,000	2%
	2040	205,000,000	8,500,000	4%
lithium	2030	52,500,000	5,500,000	11%
	2040	205,000,000	45,500,000	22%
Nickel	2030	52,500,000	1,500,000	3%
	2040	205,000,000	12,000,000	6%
Copper	2030	52,500,000	5,500,000	10%
	2040	205,000,000	44,000,000	22%

Figure 5: Impact of recycling on reducing primary demand for cobalt

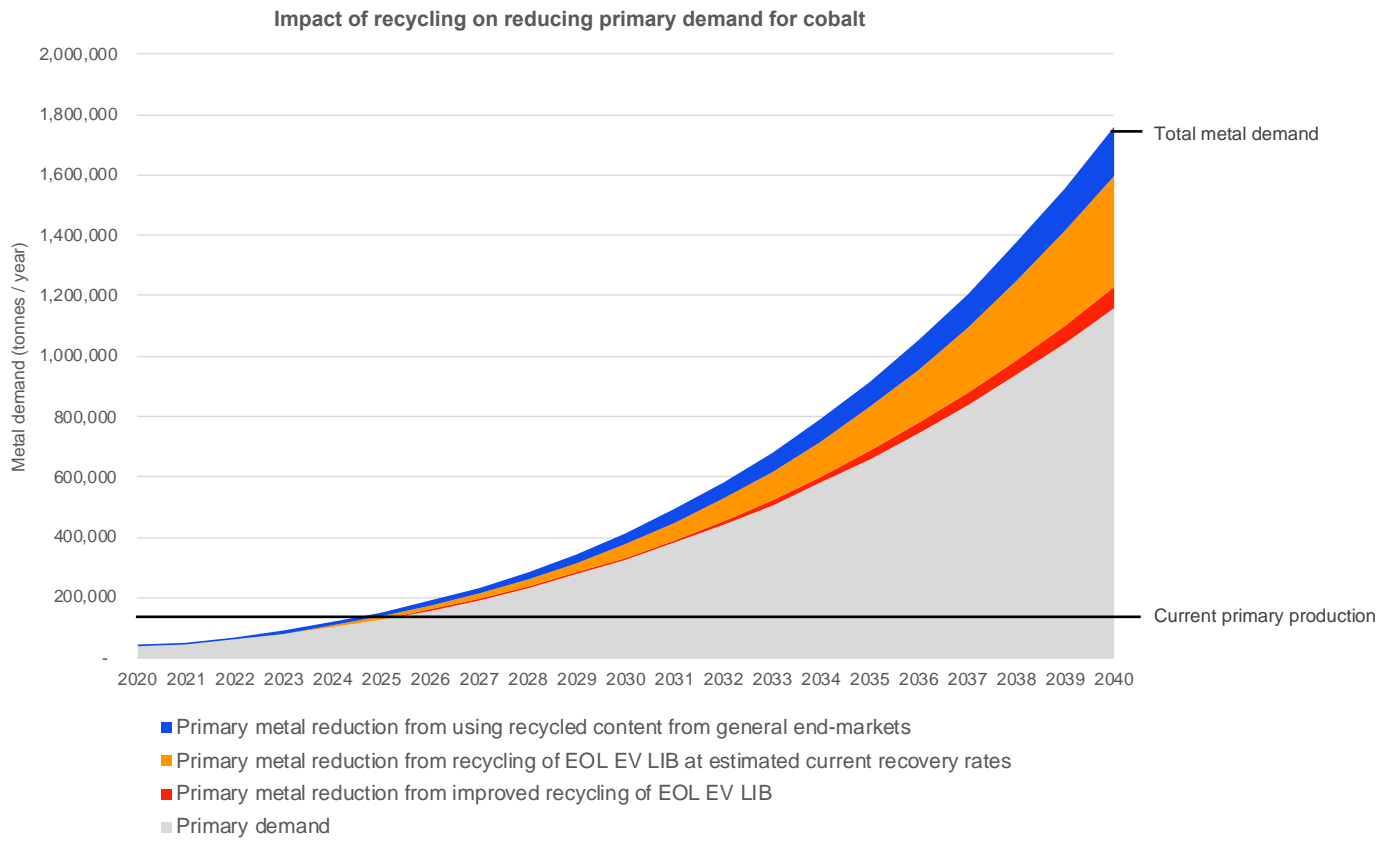


Figure 6: Impact of recycling on reducing primary demand for lithium

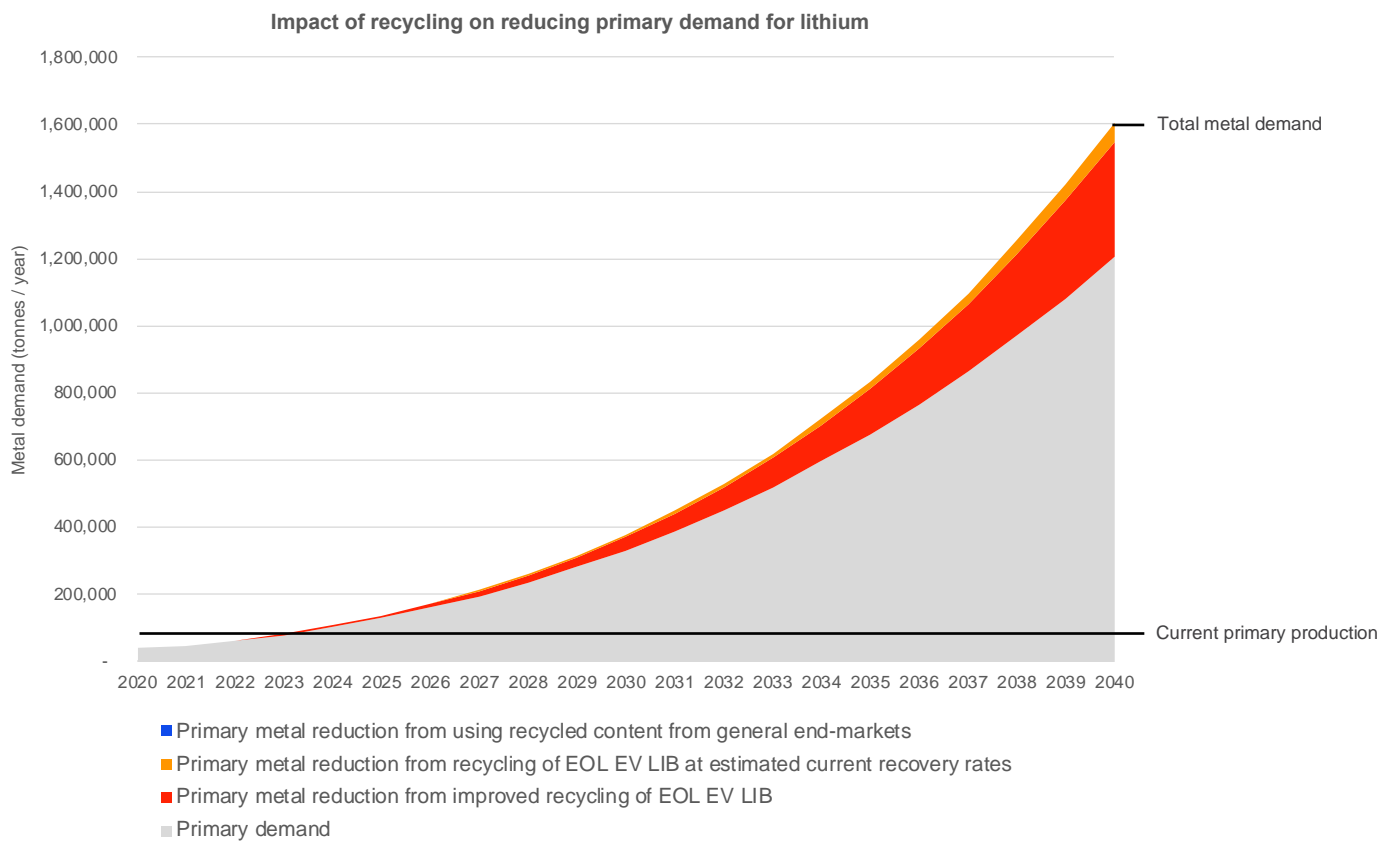


Figure 7: Impact of recycling on reducing primary demand for nickel

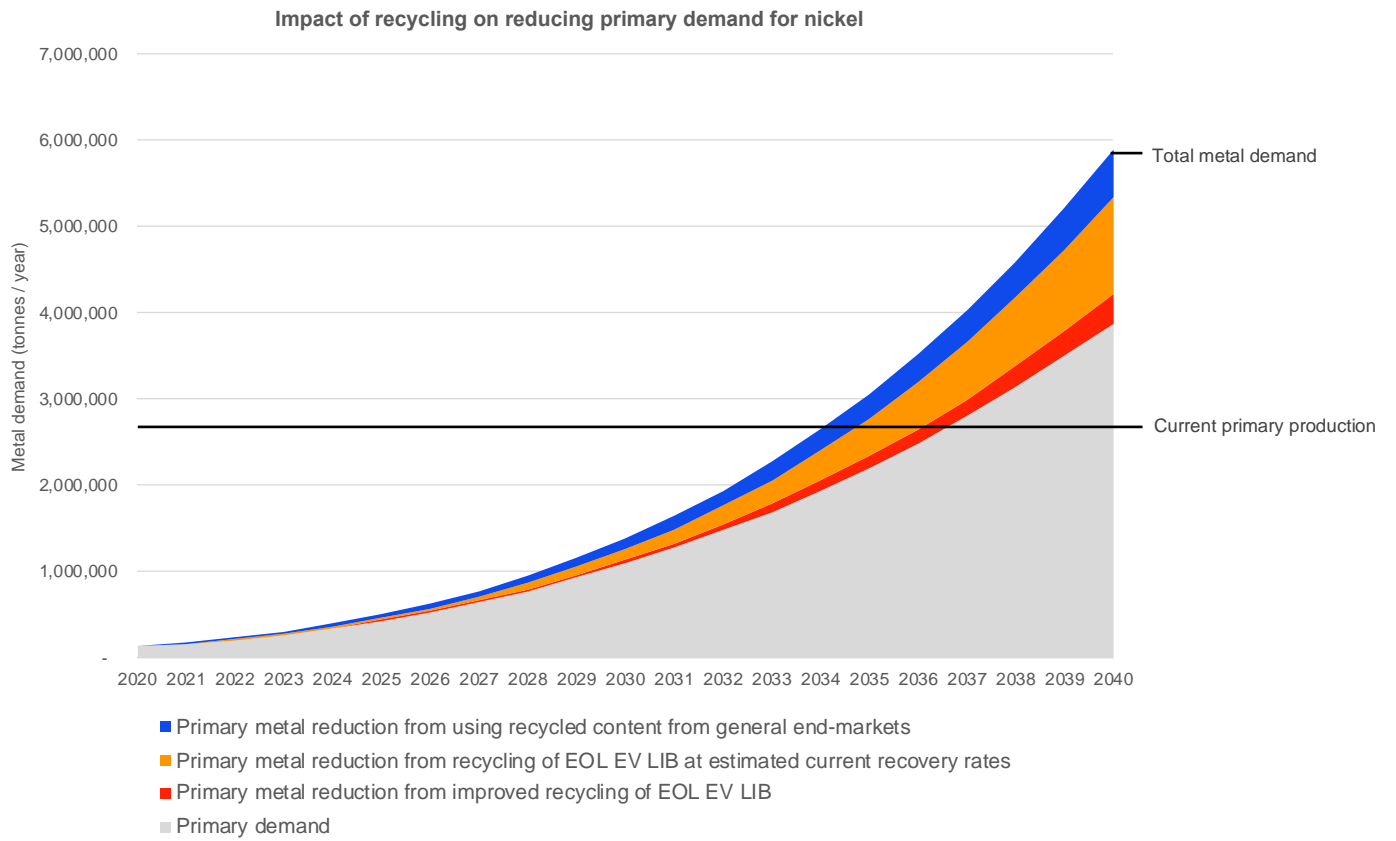
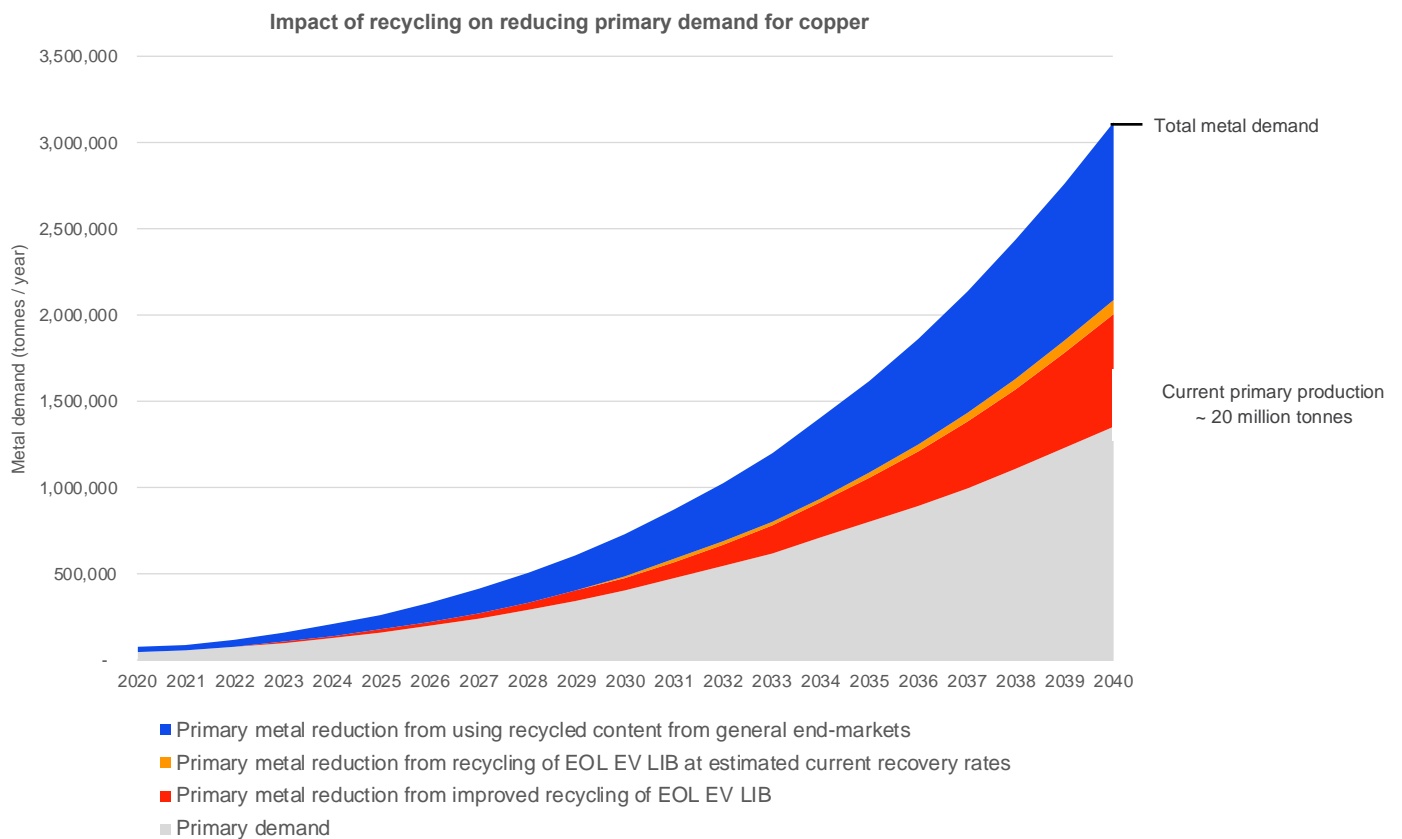


Figure 8: Impact of recycling on reducing primary demand for nickel








Part 3: Review of policy gaps and enablers for a circular economy for lithium-ion batteries

This section examines the policy gaps and potential enablers necessary to support the growth of EV battery reuse and recycling, categorised according to policy areas identified as being most significant. The high-level policy gaps and enablers for each policy area are summarised in Table 13 and outlined in further detail below.

Best practice policies for managing EV batteries broadly follow circular economy principles, including designing out waste and pollution, minimising material inputs and keeping products and materials in use for as long and as intensively as possible.¹⁰⁶ In practice, adhering to these principles involves considering higher order processes for ensuring decreased material and energy use across the economy, such as avoidance and reuse, before pursuing recycling and disposal options.

Table 13 Overview of key policy reform areas for a circular economy for LIBs

Policy area	Policy gaps and enablers
Battery collection 	<ul style="list-style-type: none"> Mechanisms to enable battery collection at EOL for use in second life applications or recycling are currently limited across jurisdictions. Battery collection rates could be improved through policies targeting enhanced stakeholder communication along the supply chain, improved traceability of batteries, incentives for users to return EVs and/or batteries to facilities connected to established take-back pathways.
Transport and logistics 	<ul style="list-style-type: none"> Safe and cost-effective transport and handling of batteries intended for second life applications or recycling are currently a significant inhibitor to uptake of these recovery pathways. Policy reform could help address these barriers by focusing on: synchronisation of cross jurisdictional requirements for dangerous goods transport to reduce administrative and cost burdens; refinement of definitions and transport requirements related specifically to EV batteries intended for recycling and reuse respectively; streamlining and centralising licencing and compliance processes for all stakeholders involved in moving and assessing EOL batteries.
Design and manufacturing 	<ul style="list-style-type: none"> The design of EV batteries presents a significant challenge for recycling. EV batteries are currently manufactured by multiple companies with divergent design practices and configurations, including variations in chemistry, size, battery shapes. While policy to enforce standardisation would address many of these issues, it may also inhibit companies' abilities to protect competitive advantage in the market from specialised design information.
Standards across the battery lifespan 	<ul style="list-style-type: none"> There is an absence of standards pertaining to evaluation criteria, methods and requirements for: battery performance and durability; State of Health; handling of used batteries (including dismantling and storage); suitability for different second life applications; and chemical labelling. While some industry standards have emerged for specific second life applications, they are limited and do not cover remanufacturing and refurbishment processes.
Definitions and frameworks 	<ul style="list-style-type: none"> Inconsistent regulatory definitions of terms such as "reuse", "waste" and "same purpose" create confusion with respect to EOL transport and processing. Clear and consistent definitions of key terms across legislative instruments, policies and relevant industries would facilitate ease of recycling and reuse operations.

¹⁰⁶ Ellen-MacArthur-Foundation. (2020). What is the Circular Economy? Ellen Macarthur Foundation <https://lithium.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy>

In addition to the instruments described in this chapter that primarily relate to government intervention, recycling and reuse schemes run by industry also play an important role. A number of large OEMs and other players along the value chain have their own business models in place that emphasise circularity, such as BMW, General Motors and the materials technology company Umicore. Given the cost of the metals required for batteries and the vulnerability to a disruption in supply associated with dependence on mining operations in other states, it makes financial sense for companies to try and recover as much value from used materials in proximate circulation as possible.¹⁰⁷

Based on the literature reviewed and stakeholder interviews, it was apparent that policy frameworks required to support the design, collection, transport and logistics, disassembly and other types of processing needed for both reuse and recycling are still underdeveloped across all jurisdictions. Although most markets have some form of policy or regulatory instrument to ensure the recycling, reuse or refurbishment of consumer electronics and industrial batteries, most markets requirements targeted specifically for EV batteries. There are, however, a number of specific policy recommendations and regulatory reviews underway that are instructive in determining relevant areas for action.

United States Context

Eight US states have EPR mechanisms and waste management laws for rechargeable batteries, however only three explicitly include LIBs. These are **California's Rechargeable Battery Recycling Act** of 2006, **New York State's Rechargeable Battery Law**, and **Minnesota's Rechargeable Battery and Products Law** of 1994. These states all ban their disposal in landfill and promote a free system for return of used rechargeable batteries. However, these measures have been criticised for inadequate enforcement of penalties for non-compliance. New York includes a penalty for violations, however fines tend to be nominal or irregularly enforced, while California and Minnesota have no penalty.

Minnesota has set non-mandatory collection targets of 90% for rechargeable battery waste, including EVs, and requires EV and battery manufacturers to co-manage waste batteries. However, the current laws and operative collection schemes in New York and California do not specifically include EV batteries, based on the presumption that EV batteries would be returned via the same channels as lead-acid batteries. However, a number of bills were proposed in California in 2018 aimed at specifically addressing EV batteries. One bill, "AB-2832 Recycling and Reuse: lithium-Ion Batteries,"¹⁰⁸ aims to establish proper EOL management for EV LIBs. It requires collaboration across state agencies to identify what is needed to enable improved reuse and recycling and promotes the establishment of a grant program for developing EOL avenues, including potential funding for battery manufacturers. The other key bill was "AB-2407 Recycling: lithium-Ion Vehicle Batteries: Advisory Group", also introduced in 2018¹⁰⁹ that proposed the establishment of a "lithium-Ion Car Battery Recycling Advisory Group" (by April 2019) which is now working to advise the Legislature on policies aimed at ensuring 90% of LIB in the state are reused or recycled at EOL in a safe and cost-effective manner. These bills have the potential to enable high collection and recycling rates of EV batteries in California.

European Union Context

The legislative frameworks for managing EV batteries at EOL are more advanced in the EU than in the United States. There are two primary EU Directives specifically targeting EV batteries: the **Batteries Directive** (2006/66/EC), which covers EV batteries that reach EOL prior to the vehicle failing, and the **End-of-Life Vehicles (ELV) Directive** (2000/53/EC), which covers batteries as part of an EOL vehicle. EOL batteries are managed in the EU under the Batteries Directive, which is translated into the legislation of all

¹⁰⁷ Kelleher Environmental (2019) "Research Study on Reuse and Recycling of Batteries Employed in electric vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries." <https://lithium.api.org/~media/Files/Oil-and-Natural-Gas/Fuels/Kelleher%20Final%20EV%20Battery%20Reuse%20and%20Recycling%20Report%20to%20API%2018Sept2019%20edits%2018Dec2019.pdf>

¹⁰⁸ California Legislative Information: AB-2832 Recycling and Reuse: lithium-Ion Batteries (2018). Available at: http://leginfo.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB2832

¹⁰⁹ Ibid

EU Member States, for the purpose of mitigating any negative impacts of batteries and waste batteries on the environment. EV batteries are categorised under the Directive as industrial batteries, and are consequently subject to the same regulations and goals as batteries for local energy storage systems and more diverse types of electric vehicles such as e-bikes. Under the EPR arrangements for this category, all producers of industrial (including automotive) batteries are required to take-back all waste batteries with no charge to end-users.

The European Commission has carried out an evaluation of the Batteries Directive that is likely to lead to a revision.¹¹⁰ With regards to collection and resource recovery, the evaluation concluded that the rapid pace of technological development and the diversity of new battery applications impacts the ability of the directive to meet objectives for collection and efficient recovery of materials potentially limiting the EU's ability to manage supply risks for raw materials. In 2020 the commission published a proposal for a new regulation to replace the Batteries Directive.¹¹¹ In line with circular economy principles, the proposal promotes a new regulatory framework that not only considers EOL but also production including responsible sourcing, use phase, and GHG emissions. Four policy options were proposed ranging from BAU to a high-level of ambition, however the Commission's "preferred option" is characterised as the "medium level of ambition option". Under this preferred option, in addition to a new LIB recycling efficiency (65% by 2025) and material recovery rates (Co 90%, Ni 90 %, Li 35 %, Cu 90% in 2025) a number of new measures are proposed that are relevant to EV batteries. This includes a new classification to differentiate EV batteries from portable and industrial batteries, and clarification on waste classifications. That is, EOL batteries are not considered waste for reuse applications, and second life batteries are considered to be new products that must therefore comply with requirements for new products placed on the market. Other measures include mandatory declaration of carbon footprint and levels of recycled content in 2025 for EV batteries, as well as information requirements on performance including durability.

The ELV Directive sets specific targets for reuse, recycling, and recovery of ELVs and their parts, including batteries.¹¹² The Directive also mandates that producers manufacture new vehicles without hazardous substances, in order to encourage the reuse and recyclability of ELVs. It also specifies that the dismantling and recycling of ELVs is carried out in an environmentally responsible way. The Directive also sets up a framework whereby EV owners can return the vehicle to an authorised facility for recovery and producers will meet the majority of costs.

The European Commission initiated a review of the ELV Directive in 2018, to ensure it is synchronised with other EU legislation dealing with waste, and account for emerging challenges and requirements created through growing waste streams such as EV batteries. In addition, an EU Innovation Deal (a voluntary cooperation agreement between the EU, innovators, and national, regional and local authorities) was set up in 2018 to specifically analyse whether existing EU laws hinder the recycling and reuse of batteries for EVs.¹¹³ The Deal, called "*From e-mobility to recycling: the virtuous loop of the electric vehicle*" is specifically examining legislative and regulatory barriers to the use of propulsion batteries in second life applications, and feasible ways of overcoming these barriers. To do this it looks at two particular areas of regulation: the Waste Regulatory Framework and the Energy Regulatory Framework. The outcome of this process will be the provision of recommendations on possible national, regional, and local regulatory barriers to the second life of EV batteries for energy storage and how to address them. The regulatory frameworks in scope include electricity market design, fees applied to storage systems, self-consumption and smart metering.

¹¹⁰ European Commission (2019) Commission staff working document on the evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC Available at: https://ec.europa.eu/environment/waste/batteries/pdf/evaluation_report_batteries_directive.pdf

¹¹¹ European Commission (2020) Proposal for a regulation of the European Parliament and of the council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 Available at: https://ec.europa.eu/environment/waste/batteries/pdf/Proposal_for_a_Regulation_on_batteries_and_waste_batteries.pdf

¹¹² Element Energy (2019) Batteries on wheels: the role of battery electric cars in the EU power system and beyond. https://lithium.transportenvironment.org/sites/te/files/publications/2019_06_Element_Energy_Batteries_on_wheels_Public_report.pdf

¹¹³ European Commission (2018) "From e-mobility to recycling: the virtuous loop of the electric vehicle" https://ec.europa.eu/info/research-and-innovation/law-and-regulations/innovation-friendly-legislation/identifying-barriers/signed-innovation-deals_en#emobility

Collection

To enable effective EV battery recycling and reuse, it is important that batteries are able to be reliably recaptured at EOL. Across jurisdictions, there is currently a lack of mature and consistent take-back pathways for car owners to return their batteries at the end of an EV's life. In the absence of strong economic drivers for car owners to return batteries at EOL and established battery collection channels, it is important that batteries are traceable throughout their lives, and that there is good information sharing along the supply chain, and stakeholder education so adequate collection mechanisms can be established.¹¹⁴ Without improved traceability and collection mechanisms there is a risk that batteries may end up in international second hand car markets. This is particularly in the case of the United States, where many damaged cars commonly end up in scrap yards, those who remove the battery may not have adequate facilities to handle them safely and without causing damage.

While the efficacy of the specific mechanism is yet to be demonstrated, the Battery Passport concept being explored by the Global Battery Alliance is an example of a type of measure that may be used to support responsible EOL management of EV batteries. The Passport, which is predicted to be in operation by the end of 2022 is "a global solution for securely sharing information and data to prove responsibility and sustainability to consumers with a "quality seal", while enabling resource efficiency across the battery life cycle."¹¹⁵ A number of technological solutions are being developed to realise this type of concept, for example, the UK company Everledger has created a blockchain application to track the provenance of battery packs and cells throughout their life cycles. Via the Alliance, it is using this technology to track EV batteries through the reuse supply chain for auto industry suppliers such as Johnson Controls and Saft and OEMs such as Audi. In 2019 they were also awarded funding by the United States Department of Energy to run two pilot programs that trace the lifecycle of LIBs using blockchain and Internet of Things technologies.¹¹⁶

Transport

The regulations around transportation and logistics associated with moving EOL EV batteries for both reuse and recycling have been identified as significant barriers. The specific issues vary considerably depending on regional and jurisdictional context, but often relate to the lack of clear and specific definitions of "waste" and "reuse" as applied to batteries.¹¹⁷ Other barriers include a lack of provisions specific to EV battery handling and transport, as opposed to other rechargeable and industrial batteries in general, and issues associated with crossing borders - both at EOL for the EV as well as prior to the end of the vehicles' life.

The EU context

While the EU is the most advanced in terms of regulating batteries, the systems established for managing their movement and transport are complex and can lead to perverse outcomes. While safe transport is paramount, a recent review of EU Directive 2008/6815 on the inland transport of dangerous goods as applied to packaging for the transportation of LIBs suggests a reassessment of these regulations is required to avoid unnecessary activities that are incurring additional cost and environmental impacts associated with transport and packaging waste.¹¹⁸ Stakeholders interviewed in this study also suggested that excessively stringent and expensive regulations may lead to the dumping of batteries.

One example of this complexity is associated with the need for the transporter to designate damaged EV batteries as either 'damaged but not critical' or 'damaged and critical'.¹¹⁹ Depending on the classification, which must be conducted by a specialised assessor, rather than the logistics service provider, there are two

¹¹⁴ International Energy Agency (IEA) Global EV Outlook 2020. Available at: <https://lithium.iea.org/reports/global-ev-outlook-2020>; European Commission (2020). *A new circular economy action plan for a cleaner and more competitive Europe*, Brussels: European Commission.

¹¹⁵ WEF (2020) World Economic Forum: Global Battery Alliance, <https://lithium.weforum.org/global-battery-alliance/action>

¹¹⁶ Roman, L. (2020) Everledger. Blockchain Battery Recycling: on track for a circular economy: <https://lithium.everledger.io/blockchain-battery-recycling-on-track-for-a-circular-economy/>

¹¹⁷ Renault Group (2020) Final report of the second innovation deal "from e-mobility to recycling: the virtuous loop of the electric vehicle" <https://group.renault.com/wp-content/uploads/2020/05/final-report-innovation-deal-on-batteries.pdf>

¹¹⁸ Ibid

¹¹⁹ McCandless, K. (2019) Still got it: How reuse and recycling can give EV batteries a new lease of life, Available at: <https://lithium.automotivelogistics.media/still-got-it-how-reuse-and-recycling-can-give-ev-batteries-a-new-lease-of-life/37938.article>

different supply chain options.¹²⁰ For the former, the battery pack must be transported in a UN-approved container, including packaging material that prevents the evolution of heat, whereas the latter requires a specialised steel container for transportation, including a built-in fire extinguishing system. In both cases, the container must be labelled with the UN Class 9 label for LIBs and a UN Material Data Safety Sheet. A certified high-voltage expert must also be present to uninstall the battery from the vehicle and to package the battery into the container.

If a battery is classified as EOL, the transport is subject to waste regulations, which require transporters to have specific waste-transport brokerage licenses for multiple country jurisdictions (if crossing borders) and the approval of the relevant authorities, including the specification of transport routes, in addition to meeting dangerous goods requirements such as special vehicles, equipment and specially-trained drivers.¹²¹ At present, national trucking companies often lack the licenses required to operate in other countries and transport has become largely restricted to specialised service providers that manage all activities and packaging materials required for the transportation of used EV batteries. For example, SimpLi Return provides complete logistic solutions including packaging materials and tracking along the entire waste management chain as well as combined management of all data and documentation for compliance.¹²²

Design and Manufacturing

The design of EV batteries presents a significant challenge for recycling and reuse. EV batteries are currently manufactured by multiple companies with divergent design practices and configurations, including variations in chemistry, size, battery shapes (e.g. some are a prismatic design while others are a pouch) and disassembly requirements.¹²³ Stakeholders consulted in this study highlighted that while the key companies manufacturing LIB batteries often employ a similar general design, the chemistries are likely to differ, and LIB batteries from a range of applications are usually recycled in the same facilities. As noted above, because EV battery chemistry is usually not labelled, battery refurbishers and recyclers find it difficult to determine the kind of batteries they are receiving. In addition, EV batteries also come with a battery management system (BMS) that regulates the primary functions of the battery. Because BMSs are not standardised, consistent approaches cannot be used to test battery health contributing to higher processing costs.¹²⁴ This is particularly problematic in the case of reuse, which requires batteries to be reassembled into different configurations with controllers that are specific to the battery and application.

The literature and engagement with stakeholders revealed that a current barrier to standardisation is the misalignment with strategies to maintain competitive advantage in the market.¹²⁵ There are advantages associated with OEMs protecting specialised information about diagnostics, monitoring, BMSs and chemistries. While enforcing standardisation through regulation would address many EOL processing issues, they may have significant financial consequences for some OEMs. These factors should be considered when evaluating the relative advantages and disadvantages of regulation and policy that supports EV battery recycling by industry wide recycling schemes managing batteries from OEMs across the jurisdiction versus OEM managed schemes (whether in house or by third party recyclers). The absence of regulations requiring battery standardisation will also have ramifications for battery reuse in applications such as energy storage, where direct partnerships between specific OEMs and energy companies may be more probable than energy companies sourcing multiple different second-life EV batteries.¹²⁶

¹²⁰ Kelleher Environmental (2019) Research Study on Reuse and Recycling of Batteries Employed in electric vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries.

¹²¹ Ibid

¹²² McCandless, K. (2019) Still got it: How reuse and recycling can give EV batteries a new lease of life, <https://lithium.automotivelogistics.media/still-got-it-how-reuse-and-recycling-can-give-ev-batteries-a-new-lease-of-life/37938.article>

¹²³ Olsson, L., Fallahi, S., Schnurr, M., Diener, D., and P. van Loon. (2018). "Circular Business Models for Extended EV Battery Life." Batteries, 4, 1-15. doi:10.3390/batteries4040057

¹²⁴ Ibid

¹²⁵ Olsson, L., Fallahi, S., Schnurr, M., Diener, D., and P. van Loon. (2018). "Circular Business Models for Extended EV Battery Life." Batteries, 4, 1-15. doi:10.3390/batteries4040057; Kelleher Environmental (2019) Research Study on Reuse and Recycling of Batteries Employed in electric vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries.

¹²⁶ Davies, T., Mullerova, A., and Rangan, A., (2020) The Legal Frameworks for the recycling of electric vehicle Batteries, Birmingham University: College of Law

Standards across the battery lifespan

An absence of standards for a range of factors related to EV batteries is commonly cited as a key barrier to the development of recycling and reuse across jurisdictions.¹²⁷ Some of these include:

- The performance and durability of first and second life EV batteries,
- Clarity and evaluation criteria for what constitutes State of Health (SOH) and EOL
- Handling of used batteries, including safe discharge, dismantling and storage
- Criteria for determining suitability of second use applications at EOL
- Labelling for material and chemical composition of sealed batteries

There are some examples of standards emerging, for example in 2018 UL, an accredited standards developer based in the US and Canada, published *Standard for Evaluation for Repurposing Batteries* (UL 1974).¹²⁸ This standard specifies methods used to assess the safety and performance of batteries, modules, and cells from used EVs for the purpose of use in second life applications, such as energy storage and other applications for used battery components. The standard addresses the processes of sorting and grading battery packs, modules, cells and electrochemical capacitors. It also includes requirements for specific applications of repurposed battery systems and those utilising repurposed battery pack components. This standard does not, however, cover remanufacturing and refurbishment processes.

Definitions and frameworks

At present, definitions of certain terms including “waste” and “reuse”, and “same purpose”, lack the clarity and specificity required to adequately regulate EV batteries destined for second life and recycling.¹²⁹

Reuse

In relation to second-life batteries in the EU, Renault Group’s review as part of the Innovation Deal determined that the current regulatory framework is unclear and unfit for large-scale reuse of EV batteries.¹³⁰ Specifically, they note that the Waste Framework Directive (2008/98/EC, as amended) and the Batteries Directive (2006/66/EC, as amended), do not address the key barriers identified for the viability of second-life battery markets.

They found that because reuse and the second life of batteries are currently not considered specifically in the Waste Framework Directive, there is not a clearly defined legal framework within which second life batteries can develop. In the absence of specific provisions general rules for ‘other batteries’ apply in relation to reuse and preparation for reuse. One implication of this is that OEMs would remain responsible for the battery until it is eventually scrapped or recycled, regardless of its application in between, due to extended producer responsibility provisions. The review conducted as part of the Innovation Deal specifically noted that:

1. To provide greater certainty around the legal status of batteries as “waste” it is proposed that the European Commission 1. clarifies the notion of “waste” and 2. uses that definition to develop models to enable the transfer of materials from one holder to another holder for reuse. In particular, they propose that a battery at the end of its first life should not qualify as a waste when the producer (of the battery or EV) intends to ensure its reuse for given purposes that fits the battery’s capacity and design.

¹²⁷ Elkind, E. (2014). Reuse and Repower: How to Save Money and Clean the Grid with Second-Life electric vehicle Batteries. UC Berkeley: Berkeley Law. <https://escholarship.org/uc/item/32s208mv>; Gaines, L., Richa, K., & Spangenberg, J. (2018). Key issues for Li-ion battery recycling. MRS Energy & Sustainability, 5.; Kelleher Environmental (2019) Research Study on Reuse and Recycling of Batteries Employed in electric vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries; Engel, LITHIUM., Hertzke, P., and Siccardo, G. (2019) Open interactive popup Second-life EV batteries: The newest value pool in energy storage <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage#:~:text=In%20September%202018%2C%20Renault%20announced,largest%20in%20Europe%20to%20date>.

¹²⁸ UL. UL 1974: Standard for Evaluation for Repurposing Batteries. Available online: https://standardscatalog.ul.com/standards/en/standard_1974

¹²⁹ Renault Group (2020) Final report of the second innovation deal “from e-mobility to recycling: the virtuous loop of the electric vehicle” <https://group.renault.com/wp-content/uploads/2020/05/final-report-innovation-deal-on-batteries.pdf>

¹³⁰ Ibid

2. Legal uncertainties remain regarding the interpretation of “reuse” and “same purpose” used by the EU legislation on waste. Article 7 of the ELV Directive states that “Member States shall take the necessary measures to encourage the reuse of components which are suitable for reuse”, reuse is defined under Article 2(6) of the Directive, as “any operation by which components of end-of life vehicles are used for the same purpose for which they were conceived”. However, there remains an absence of criteria to define what the “same purpose” means. If this notion were strictly adhered to, the definition of “re-use” could not apply to multiple reuse options. To rectify this, it is proposed that “re-use” and “same purpose” are stabilised as terms that account for the purpose of EV batteries as delivering the storage and delivery of electrical power, whether in an EV or in a power storage system. In the absence of the proposed clarifications, some public authorities may consider that EV batteries at EOL would automatically qualify as waste.

Quality assurance and liability for second life battery applications

The uncertainty around liability for damage to and performance of second-life batteries may be a disincentive for reuse of EOL EV batteries, compared to new batteries. This has been particularly noted for energy companies purchasing EOL EV batteries from OEMs for energy storage or grid service applications, which are the most common reuse applications at present.¹³¹ There are currently no regulatory guarantees regarding the quality of second-life-batteries or performance, and while there are very few industry standards addressing disclosure around SOH or battery-management systems, or performance specifications for specific applications.¹³² It is also unclear in the case that a second-life battery results in damages, whether the OEMs are liable. As a result, some OEMs are reluctant to allow their EV batteries to be reused in grid storage applications. Moreover, because second life EV batteries are a new technology, there is a lack of data about performance and risks required for insurance companies to calculate premiums.¹³³ This could result in higher premiums being set for property owners using this energy storage option. In addition to more stringent standards, some of these risks may be mitigated if OEMs decide to retain ownership of the batteries and lease them to energy companies for the duration of their second life, thus retaining the materials for their potential recycling value and maintaining liability.¹³⁴

Issues associated with liability and reluctance to purchase second life batteries are, however, somewhat context dependent. Interviews conducted with stakeholders that have knowledge of the EU context suggested that some of these issues may be mitigated by commitments in the EU energy industry to responsibly source batteries to ensure that sustainability and labour issues in the supply chain are prioritised in procurement. As a result, some EU OEMs have established relationships with energy companies to take second life batteries. For example, in 2018 Renault announced its Advanced Battery Storage Program, involving several partners in the energy sector and is expected to produce 70 megawatt/60 megawatt-hours from used EV batteries in the EU by 2020.¹³⁵ BMW has also established similar partnerships with energy companies.¹³⁶ However, due to limited volumes of batteries currently reaching EOL, it is uncertain whether or not this will become common practice at a greater scale.

¹³¹ Catton, J.LITHIUM.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). Design and Analysis of the Use of RePurposed electric vehicle Batteries for Stationary Energy Storage in Canada. Batteries, 5(14), 1-19

¹³² Kelleher Environmental (2019) Research Study on Reuse and Recycling of Batteries Employed in electric vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries.

¹³³ Catton, J.LITHIUM.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). Design and Analysis of the Use of RePurposed electric vehicle Batteries for Stationary Energy Storage in Canada. Batteries, 5(14), 1-19

¹³⁴ Engel, LITHIUM., Hertzke, P., and Siccardo, G. (2019) “Open interactive popup Second-life EV batteries: The newest value pool in energy storage” <https://lithium.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage#:~:text=In%20September%202018%2C%20Renault%20announced,largest%20in%20Europe%20to%20date>

¹³⁵ Ibid

¹³⁶ Envirotec (2020) “Energy storage firm partners with BMW for EV battery second use”, <https://envirotecmagazine.com/2020/10/16/energy-storage-firm-partners-with-bmw-for-ev-battery-second-use/>

Conclusions and Recommendations

To help minimise the adverse social and environmental impacts of mining associated with LIBs for EVs, this report has evaluated available strategies to minimise demand for EV batteries and primary metals. The strategies examined include reduced demand from the reduction of private car ownership, the reuse of EV LIBs in second life applications and the recovery of metals for new battery manufacturing through recycling.



Promoting effective recycling

Our analysis determined that while recycling rates from EOL EV LIB are currently low, particularly for copper and lithium, there is technological capability to recover all four metals at rates above 90%. Moreover, we found that recycling has the potential to reduce primary demand compared to total demand in 2040, by approximately 25% for lithium, 35% for cobalt and nickel and 55% for copper. It also identified that in future, EOL EV LIB is likely to be the most viable pathway to source secondary metals for cobalt, lithium and nickel, while copper is likely to come from general copper recycling routes. These findings highlight the importance of maintaining and improving recovery rates of these metals from EOL EV LIB and developing strong policies to support these activities.



Reducing demand for new batteries

While recycling is a very important strategy that can support a significant reduction in demand for primary materials, it is clear that a broad range of strategies are needed. Based on circular economy principles, policy should focus on reducing demand for batteries through enabling greater uptake of car sharing and public transport and ensuring viable second life uses for EV LIBs where possible, rather than exclusively pursuing recycling pathways.

EOL EV LIB are able to be effectively reused for stationary storage, fast charging stations, refurbishment for use in other types of vehicles, and even EV-to-EV applications. The most significant market is likely to be the use of second life EV LIB in grid storage applications, with potential lifetimes of approximately 12 years. Policy is required to incentivise, enable and reduce the risk associated with the development of these secondary markets.



Policy recommendations

To enable greatest demand reduction through EOL EV LIB refurbishment, reuse and recycling, the following key areas of intervention should be prioritised:

- **Collection:** Improved collection of EV LIBs at EOL could be enabled through stronger policy supporting traceability over battery lifetimes, supported by good information sharing along the supply chain and increased efforts in stakeholder education from OEMs to EV consumers.
- **Transport:** The clarification of definitions including “waste” and “reuse” as applied to EV LIB batteries in safe handling and transport regulations within and across jurisdictions, and specific, standardised protocols for transporting and handling EV LIB batteries intended for second life applications are required to overcome current transportation barriers.
- **Design:** While the standardisation of design practices and configurations for EV LIB, including in chemistry, size, shape and disassembly requirements would enable, reuse and recycling to be more efficient and scalable, issues of commercial confidence may make this solution unviable. Alternatively, greater incentives to improve ease of disassembly and ensure those processing batteries for reuse and recycling have adequate information about the battery would aid in market development, and contexts where OEMs have established partnerships with second life battery users, such as energy companies.

- **Standards:** Improved standards are required that pertain to: methods used to assess battery safety and performance for second life applications, such as energy storage; processes of sorting and grading battery packs, modules, cells and electrochemical capacitors; requirements for specific battery systems repurposed for specific applications and repurposed battery pack components; standards pertaining specifically to battery reuse and refurbishment requirements; and, recycling standards that encourage high-value recovery of all battery materials.
- **Definitions:** A clearly defined legal framework within which a second life battery market can develop should be created within each appropriate jurisdiction. This will enable consistent communication between parties along the supply chain and ensure that batteries are able to be directed to the most appropriate EOL pathway without unnecessary administrative burdens and costs.

The move towards renewable energy systems, and particularly the transition to EVs, provides important opportunities to reconsider the social and environmental sustainability of supply chains associated with key battery materials. This report has shown that demand for metals used for the development of renewable energy technologies can be effectively reduced. With the right policies in place, refurbishment, reuse and recycling can be important strategies for a future circular battery economy.

