COBALT INSTITUTE
enabling technology, advancing society

Towards a Circular Value Chain of Cobalt

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EXECUTIVE SUMMARY

Launched in 2022, the Cobalt Institute's Circular Economy Work Programme aims to investigate circular economy models across the entire cobalt value chain while providing actionable recommendations to achieve a **sustainable and inclusive cobalt industry.**

The following report is structured across **three axes** and focuses on hotspots in the cobalt value chain where resources are lost, underutilised, or at risk of causing social and environmental harm. This led to a focus on cobalt **extraction, product design,** and the **end of life of consumer products.** A total of **ten circular solutions** are proposed in the report, and assessed according to their capacity to generate social and environmental benefits, as well as their capacity to generate tangible value for stakeholders.

REGENERATING NATURAL SYSTEMS VIA ZERO WASTE COBALT MINING

The cobalt mining industry can reduce the environmental impact of mining waste, while creating shared value for local communities and ASM miners by deploying **electrified and smart** mining technologies, **re-processing extractive waste**, remediating mine sites with **nature based solutions**, and **sequestering CO_2 with mine tailings.** These circular solutions provide a vision for achieving zero waste, regenerative cobalt mining. The potential of nature-based solutions is demonstrated by the case study of Electra BMC's support of indigenous communities in Ontario confronting the impact of legacy mining waste and fostering nature-based livelihoods.

MAXIMISING RESOURCE VALUE BY EXTENDING THE LIFE OF COBALT PRODUCTS

Extending the lifespan of cobalt products can be achieved by **designing long-lasting batteries, remanufacturing** EV batteries, and **repurposing** batteries for less demanding applications. These three solutions have potential environmental benefits and can unlock new business models associated with longer-lasting EV batteries, as illustrated by the million-mile battery supplied by CATL.

DESIGNING OUT WASTE AND POLLUTION THROUGH INTEGRATED BATTERY DESIGN AND RECYCLING

Improved collection and recycling of e-waste and EV batteries can reduce waste generated by cobalt products at end-of-life and minimise negative environmental impacts. By **improving the collection** of waste products, **optimising their recycling** to recover high-value materials, and **incorporating the recovered material into future products**, circularity can be integrated into the last stage of the cobalt value chain. Fairphone's e-waste neutrality initiative, which involves taking back or compensating for the equivalent of all *Fairphone 4* units sold in discarded electronic products, serves as a case study for new partnerships in e-waste collection and sorting for recycling.

The transition to a circular economy is an ongoing process, and primary cobalt will still be essential in coming decades to meet the increasing demand for climate-friendly technologies, especially for energy storage in e-mobility. The move towards circularity has major potential to create shared value for people and the planet by recovering cobalt from waste streams and maximising the value of cobalt products in use.

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ABBREVIATIONS AND ACRONYMS

ACRONYM	DESCRIPTION
AMD	Acid Mine Drainage
ASM	Artisanal and small-scale mining (cobalt)
BaaS	Battery as a service
CATL	Contemporary Amperex Technologies Co., Limited
Co	Cobalt
CRM	Critical raw material
Cu	Copper
DRC	Democratic Republic of the Congo
EPR	Extended producer responsibility
ESS	Energy storage system
EU	European Union
EV	Electric vehicle
GHG	Greenhouse Gas
HPAL	High pressure acid leaching
LCA	Life cycle assessment
LME	London Metal Exchange
LSM	Large-scale mining (cobalt)
NbS	Nature-based solution
Ni	Nickel
NMC	Nickel manganese cobalt
OEM	Original equipment manufacturer
PCAM	Precursor cathode active materials
USD	United States Dollar
WEEE	Waste from electrical and electronic equipment

INTRODUCTION

Cobalt is an essential material for the global economy and widely used in various applications, including in the production of batteries for electronic devices and vehicles. With the shift towards decarbonised electrification, the demand for cobalt is expected to grow significantly in the coming years. Implementing the principles of a circular economy can help to ensure this transition is sustainable and creates value for all stakeholders involved in the cobalt value chain.

GLOBAL CONTEXT: WHY DO WE NEED TO MOVE TOWARDS CIRCULAR ECONOMY?

In the past few decades, there has been a decline in global wildlife populations and a breakdown in the Earth's climate system, leading to an increase in extreme weather events (IPCC, 2022). At the same time, inequality and poverty remain major issues, with 700 million people living on less than 2 USD a day (World Bank, 2022).

Average ore grades for the bulk metals such as copper and nickel are steadily decreasing with time, as easily accessible high-grade deposits are exhausted around the globe (Northey, Mohr, Mudd, Weng, & Giurco, 2014). This leads to increasing energy intensity of mining and greater mining waste. As cobalt is usually extracted as a by-product of the bulk metals, its market is also confronting the limits of business as usual and facing significant price volatility. The high cost of cobalt has caused **OEMs to seek substitutes** in their battery production, while consumer brands are under pressure from NGOs to substitute cobalt due to concerns about **human rights abuses** in the Democratic Republic of Congo (Amnesty International, 2016).

Given these challenges, **the cobalt industry requires a new economic paradigm** to sustainably match supply with demand.

AMBITION

The Cobalt Institute's Circular Economy Work Programme was launched in 2022 to explore circular economy models across the cobalt value chain and provide recommendations to make the industry more sustainable. The programme takes a comprehensive approach to the circular economy, focusing on the lifecycle of cobalt products, with the goal of regenerating natural ecosystems, reducing waste and pollution, and maximising the value of scarce resources.

The report focuses on the key areas in the cobalt value chain where resources are wasted, underutilised, or at risk of social and environmental harm. **Most cobalt losses** in the global economy occur **during extraction or at the end of the life of consumer products**, within tailings and landfilled batteries. **Improving cobalt mining and recycling** thus offers the greatest potential for recapturing lost resources and returning them to the value chain, while **eco-design and reusing** cobalt products, particularly batteries, can increase their lifespan and reduce the demand for primary and secondary cobalt supplies.

OUTLINE

To describe this vision of a circular cobalt value chain, this report is divided across **three axes**, focusing on cobalt *extraction*, *use*, and *recycling* respectively. **Ten circular solutions** that contribute to bringing each axis to life were explored in this study, as highlighted in Figure 1.

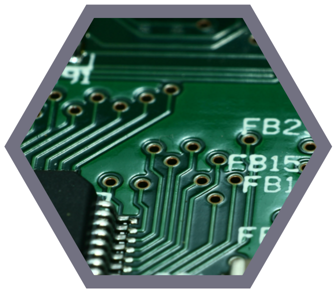
These solutions were assessed according to their ability to create social and environmental benefits, as well as their feasibility and potential to offer tangible value for real world stakeholders.

Regenerating Natural Systems via Zero-Waste Cobalt Mining

- Smart and Electrified Cobalt Mining
- CO_2 sequestration via mine tailings
- Remining recovery of metal via the remediation of mining waste sites
- **Remediating mine sites with nature-based solutions**

Maximising Resource Value by Extending the Life of Cobalt Products

- **Life extension by design in NMC batteries**
- Battery Repurposing
- Battery Remanufacturing



Designing out Waste and Pollution through Integrated Battery Design and

- Use of recycled cobalt in battery design
- **Collection, sorting and recycling optimisation**
- Battery as a service and other battery return schemes

Figure 1. The ten circular solutions

Each innovative axis is accompanied by a case study based on interviews with people involved in its implementation and on desktop research. The ambition here is to showcase the key factors that drive and hinder the implementation of circular solutions in practice, in hopes that these best practices can be replicated in other locations.

1. REGENERATING NATURAL SYSTEMS VIA ZERO WASTE COBALT MINING

The clean energy transition cannot rely solely on recycled materials, and primary metals like cobalt will be necessary for renewable energy generation and storage. Primary cobalt will need to make up most of the supply for battery storage until around 2040 when devices meet their end of life and become recyclable (KU Leuven, 2022). Given this pressing need for primary cobalt, the mining industry must play its part in building out a circular cobalt value chain.

The following innovations allow the cobalt mining industry to **improve cobalt recovery** and **reduce its environmental impact**, while also creating shared value for local communities and ASM miners. Ideally, all four solutions could help transform cobalt extraction to a **zero waste mining** industry that can help regenerate natural systems. While all four solutions in this axis improve the environmental performance of cobalt mines, **remediating cobalt mines with nature-based solutions (NbS)** has the greatest potential of social and environmental benefits.

1.1. PROPOSED CIRCULAR SOLUTIONS

1.1.1. Smart and electrified cobalt mining

Several digital and electrified innovations are beginning to enable the shift from a linear model of cobalt mining powered by fossil fuels towards a more circular model powered by renewable energy and that **minimises waste and greenhouse gas (GHG) emissions.**

Cobalt mines have an opportunity to deploy electric mining equipment including trucks, drills, and processing equipment, which could all be powered by renewable energy. Underground mines are already rapidly transitioning to battery powered equipment, which reduces costs related to ventilation due to the lack of tailpipe emissions.

However, the underinvestment in hydroelectric stations and transmission maintenance in the DRC Copperbelt (ABB, 2017) and the use of coal for electricity in Indonesia remain a concern for reducing emissions by electrifying cobalt mining (Benchmark Mineral Intelligence, 2022).

Zero waste cobalt mining is also being enabled by digital technologies, such as improved access to geological data and sensing technologies for **feedstock sorting**, allowing for **"smarter mining".** Anglo American estimates that mineral processing using bulk ore sorting and course particle recovery offer 20% savings in energy and 10% in water demand (Anglo American, 2023).

Smart and electrified cobalt mining can thus **reduce operating costs** but require large capital investments from corporations and national governments. Investments in renewable energy to power cobalt mines can also have a positive impact on local communities if this **energy is shared via community benefit agreements.**

1.1.2. CO_2 sequestration via mine tailings

Cobalt has the potential to drive global decarbonisation by enabling permanent carbon sequestration through mineral carbonation at cobalt mines. Mineral carbonation accelerates the naturally occurring geological cycle which stores carbon in solid mineral form and is well suited to geologies where cobalt is mined as a by-product of Ni. The global occurrence of suitable deposits for mineral carbonation is presented in Figure 2.

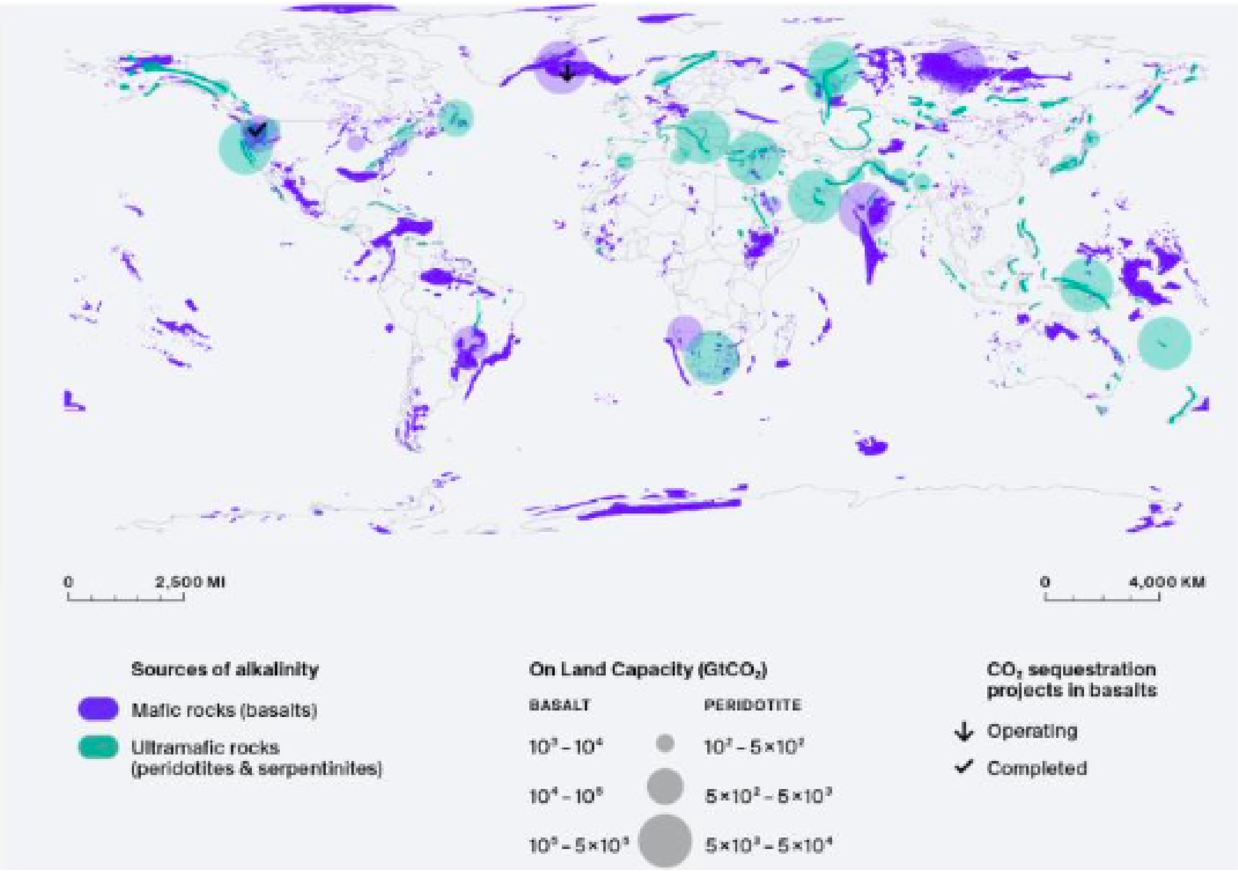


Figure 2. Locations & distributions of carbon mineralisation resources (Sandlow, et al., 2021)

By using calcium and magnesium minerals in mine tailings to permanently store carbon, mineral carbonation can offer mining sites significant potential to combat global warming by sequestering CO_2, as well as potential to **generate additional revenue** by extracting both Ni and Co from tailings (Power, Dipple, Bradshaw, & Harrison, 2020).

Global mine tailings have the potential to remove up to **400 million tonnes of CO_2** from the atmosphere annually (Wilson, et al., 2014). However, this could lead to an increased land use footprint for cobalt mines and to new environmental and social externalities. **Using cobalt mine tailings to sequester CO_2** will also require well-adapted carbon accounting methods and fiscal incentives to become economically viable.

1.1.3. Remining

Most cobalt is mined as a by-product of copper and nickel, and mining operations often prioritise concentrating nickel and copper rather than cobalt. As a result, sizable cobalt resources are lost to tailings deposits around the world. In the Congo Copperbelt, the world's largest cobalt producing region, certain processing plants designed for oxides are not well suited for treating increasing amounts of Cu-Co bearing sulphides, resulting in elevated levels of **Acid Mine Drainage** (AMD), which poses a significant environmental and health risk.

Remining involves reprocessing tailings and slags to recover the cobalt they contain, while also valorising other by-products such as sulphur and bulk materials to remediate the site. This solution represents a major **win-win opportunity** for the mining industry, with the potential to create significant **economic value** through the sale of cobalt while also dramatically reducing the **environmental and health risks** associated with mining waste.

Remining for cobalt has the potential to combat pollution at legacy mine sites, however in certain scenarios may also be more energy intensive than conventional mining. Remining can deliver clear economic value by increasing global cobalt supply, with **over one million tonnes of cobalt identified in tailings and slag deposits.** However, scaling this approach faces challenges related to feedstock complexity and legal liabilities surrounding mining waste.

1.1.4. Remediating mine sites with nature-based solutions

Over the lifespan of a cobalt mine, numerous processes can place biodiversity at risk by driving land use changes or emitting hazardous elements. Many of the world’s cobalt mines are surrounded by areas facing environmental degradation, such as the miombo woodlands in the DRC (Sikuzani, Muteya, & Bogaert, 2020), or the rainforests of Sulawesi in Indonesia.

The cobalt industry can face these challenges by using nature-based solutions. Through natural processes such as **phytoextraction**, plants known as hyperaccumulators can be used to **extract or stabilise cobalt in contaminated soils**, while **promoting ecosystem services.**

This process of phytoextraction is detailed in Figure 3 for nickel recovery, the same process could also be envisioned for cobalt. This works to depollute soils over extended timeframes, as hyperaccumulator plants withdraw metals from the ground and are repeatedly harvested, dried and either burnt or chemically leached to concentrate the Ni-Co into “bio-ore”. The bio-ore can then undergo conventional processing and refining techniques. Over several decades, Ni-Co is removed from the soil which can then be used for farming, agroforestry, or rewilding.

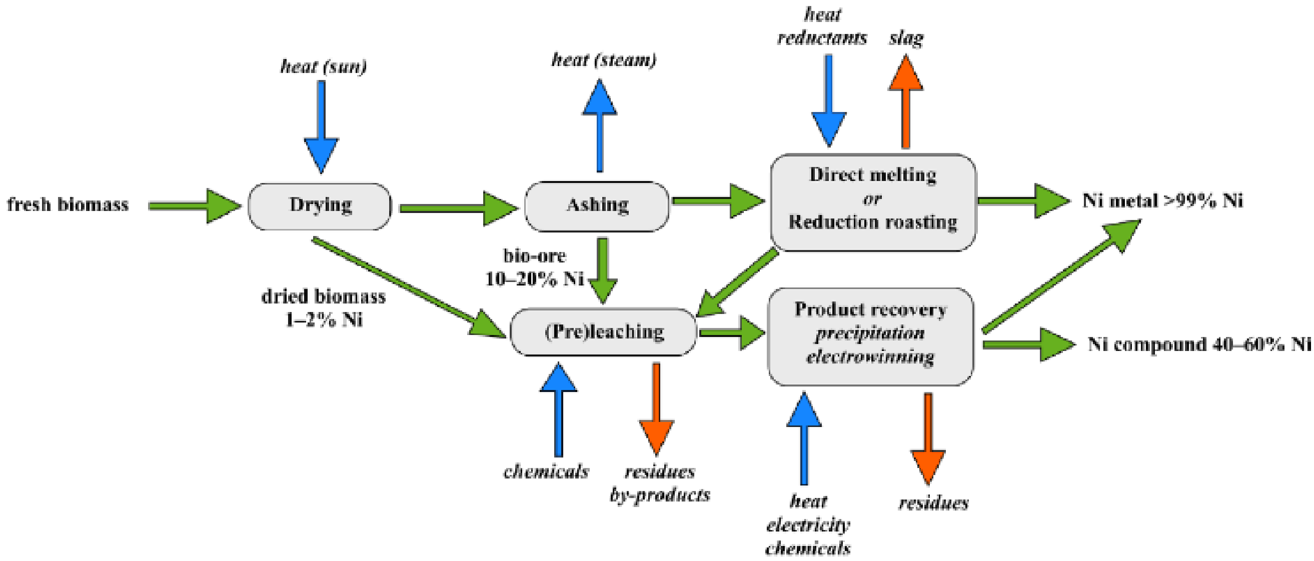


Figure 3. Flowsheet for phytoextraction of Ni-Co (Ent, Baker, & al., 2015)

By removing or stabilising metals from damaged environments, NbS can create local economic and social opportunities after mine closure and allow for **nature-based enterprises** to replace mining in the local economy. These solutions can be empowering for mining impacted communities if deployed under the framework of **community resource management.**

Nature-based remediation of cobalt mines can be enabled by the fact that mining companies already have **legal responsibility to rehabilitate mine sites** as part of the permitting processes in place. However, sustainably implementing NbS requires deep knowledge of **each mine's unique environment,** which is logistically time-consuming.

1.2. CASE STUDY OF MOST PROMISING CIRCULAR SOLUTION: ENABLING NATURE-BASED ENTERPRISE IN THE TOWN OF COBALT, ONTARIO

While all of the circular solutions in this section have the potential to improve the economic, social and environmental performance of the cobalt value chain, the case study of Electra Battery Materials' support of a local nature-based business demonstrates the **potential of nature-based solutions to create lasting social and environmental benefits.**

Electra BMC operates near the town of Cobalt, Canada, which suffers from toxic and heavy metal pollution due to poorly managed mining waste in the area from 1903 until the 1980s. Electra entered the region in 2017, and before constructing their cobalt sulphate refinery began to consult with their five neighbouring Indigenous Peoples.

Based on their feedback, Electra launched collaborative environmental studies to understand the historic impact of mining and refining on the region. Conducting these studies built a close relationship of trust between Electra and locals and has allowed Indigenous Peoples to preserve their culture by safely foraging medicinal and culinary plants, mushrooms, and fish in the region.

Business model

The Timiskaming, one of the five neighbouring Indigenous Peoples, have founded the **Wild Basket Initiative,** which sells foraged goods to locals. This nature-based business is supported by Electra's efforts to map the biodiversity and toxicology of the local ecosystem and shows that an upfront investment in building trust and optimising environmental performance pays for itself over the long term with a **social licence to operate.**

Environmental and social benefits

Establishing baseline measurements in and around their facilities has helped Electra ensure that protocols are in place to manage environmental and health risks. It has also created a potential for **traditional knowledge** and **natural stewardship** to build **economic opportunities** in an area that has suffered from the legacy impact of poorly managed mine closure.

Replicability potential

Thousands of abandoned mine sites globally could benefit from circular solutions aimed at remediation. However, it is essential to note that every mine has a unique environment and local communities, and the business model developed by Electra cannot simply be copied and pasted to other sites. Instead, the right approach entails replicating a *business mindset* by investing the time and effort to create long-term value for business, people, and the planet.

2. MAXIMISING RESOURCE VALUE BY EXTENDING THE LIFE OF COBALT PRODUCTS

Cobalt helps in extending the lifecycle of NMC batteries and alloys thanks to its exceptional thermal stability. However, the resource is currently facing **supply risks and high price volatility** (KU Leuven, 2022). In the future, cobalt demand is expected to rise due to the deployment of electric vehicles (EV) batteries, leading OEMs, and battery producers to adopt new strategies to mitigate these risks, while generating environmental and social benefits.

The following chapter goes through three innovative circular solutions revolving around life extension by design, repurposing, and remanufacturing, in an effort to alleviate tensions on cobalt production. The three solutions can considerably reduce environmental pressures such as greenhouse gas emission and the pollution of land, soil, and water bodies. **Battery life extension by design** appears as the most impactful and feasible solution.

2.1. PROPOSED CIRCULAR SOLUTIONS

2.1.1. Battery life extension by design

The extension of the battery lifespan in its design enables to **reduce the environmental negative impacts** associated with the manufacturing of a new battery.

In a NMC battery, the **role of cobalt** is beneficial in extending its lifespan and reducing the risk of failure due to external damage or internal mechanisms. It also enables to fit smaller batteries with longer ranges due to high specific energy (Deng, Bae, Denlinger, & Miller, 2020).

The battery can be designed to last for 15 years instead of 8-10 years, by incorporating high- quality cells and modules. The extension of NMC batteries' lifecycles leads to new opportunities for OEMs to engage with customers and **generate new revenue streams**. In the automotive industry, customers can either pay their battery through an upfront payment or alternatively, rent the battery with a monthly fee, which is further explained in section 3.1.3.

In addition to designing long lasting battery, OEMs are raising **user awareness** on the impacts of the in-use phase to maximise the battery lifespan, since regular fast-charging reduces its lifespan. They provide their users advice on battery management habits. For example, Renault recommends drivers to avoid leaving an electric car parked for a long time, keeping the maximum charge below 80% and charging the battery once a week (Renault, 2021).

A long-lasting battery would enable less dependence on supply and availability regarding the extraction of nickel, manganese, and cobalt. In this sense, a study demonstrates that doubling battery lifetimes would reduce cobalt demand by 619 kt by 2050, compared with 1258 kt with state-of-the-art battery cathode technologies (Zeng, et al., 2022).

However, life extension by design remains limited by the **lack of policy incentives,** while its economic feasibility will depend on the development of new business models (i.e., presence of additional services to prolong the life of the product) and the technology, as illustrated in the CATL case study in 2.2. Additionally, in the NMC battery market, stakeholders are also switching to new chemistries to lower their cobalt consumption and associated cost, switching from NMC 111 to NMC 622 and 811.[1]

A longer lifecycle of batteries (15 years instead of 8-10) would avoid about 30 to 50% of the environmental impacts coming from the extraction and refining of critical raw materials (nickel and cobalt). Environmental extraction of these CRMs is associated with biodiversity loss, the emission of greenhouse gases, and the pollution of land and soil, water bodies and air. Cobalt and nickel refining are energy intensive and are also responsible for pollution (soil, land, water bodies and air). Prolonging the life of battery also avoids other environmental impacts related to battery manufacturing and recycling.

2.1.2. Battery repurposing

By enabling NMC batteries to have a longer lifespan, cobalt makes a second life for batteries possible through **repurposing**, which refers to the re-use of batteries into less-demanding applications.

While EV batteries with a capacity below 80% are usually recommended to be replaced, they can still be re-used in second-life applications such as **energy storage systems** (ESS) for homes and street lighting. Driven by the **Extender Producer Responsibility** (EPR), a policy approach under which producers are given various financial and/or physical responsibilities for the treatment or disposal of post-consumer products, several OEMs, including Toyota and Mercedes-Benz, are creating new partnerships with energy providers to repurpose their batteries (Utility Dive, 2022).

With a global potential of **second-life battery supply** expected to reach **112 GWh/year in 2030**, repurposing could **generate revenue for OEMs** and collectors (McKinsey, 2019). With a lower cobalt content in batteries, the **economic interest of recycling** is decreasing, and repurposing might be a viable alternative for OEMs and collectors. However, a robust system needs to be put in place to ensure **efficient use and traceability** of repurposed batteries and to prove their profitability at larger scales.

The **perception of repurposed batteries on consumer-end** will need to improve in order to be a cost-competitive solution, as price of new lithium-ion batteries is falling quickly while their performance is also improving. Large-scale repurposing is also limited by a lack of **policy incentives**, and would need better policies to encourage battery manufacturers and OEMs to prioritise re-use before recycling.

Repurposing avoids environmental impacts associated with the production of new batteries for ESS, which were already mentioned in 2.1.1, and are related to raw materials extraction, refining, manufacturing, recycling.

[1] NMC 111 refers to 33% Nickel, 33% Manganese, and 33% Cobalt ; NMC 622 refers to 60% Nickel, 20% Manganese, and 20% Cobalt ; and NMC 811 refers to 80% Nickel, 10 % Manganese, and 10% Cobalt

2.1.3. Battery remanufacturing

In contrast with repurposing, remanufacturing consists in **re-using a battery for the same application** by dismantling the battery pack, performing quality tests on modules and cells, and repackaging the battery.

By replacing the damaged battery components instead of the entire battery, remanufacturing **prolongs the life of batteries.** Several OEMs are implementing remanufacturing, such as Renault which plans to sell 200 MWh of second life batteries by 2030 (Renault Group, 2020).

In order to create a cheaper, faster, and less energy-intensive remanufacturing process, careful consideration must be given to **battery design**. Permanent assembly methods, such as spot- welding or gluing, make it difficult to dismantle batteries. However, designing an easily dismantlable battery can generate new challenges, leading to a decrease in battery performance, ultimately declining its desirability for end-consumers (Siret, 2022). As a result, some battery producers prefer to focus on the design of high-quality cells and high-preforming modules in the battery, rather than remanufacturing.

Battery history is a crucial factor in predicting a battery's second life and can hold useful information for remanufacturers. The European Union is discussing the creation of a **battery passport** to record the service life of a battery cell. However, access to battery history can be a challenge when it comes to protecting the driver's personal data, which includes daily trip lengths and charging habits, and requires further clarification. There is also a need to prevent access to sensitive information on the battery design to protect the intellectual property of both battery producers and cell manufacturers.

Similarly to repurposing and life extension by design, remanufacturing **avoids environmental impacts** associated with virgin raw material extraction as well as with the design of new batteries and reduces negative impacts by enabling instead the recovery of battery components such as modules and cells. Despite its benefits, this solution **needs clearer policy incentives** to enable its large-scale feasibility.

2.2. CASE STUDY OF MOST PROMISING CIRCULAR SOLUTION: THE MILLION-MILE BATTERY BY CATL

While the three circular solutions in this section can improve the economic, social and environmental performance of the cobalt value chain, CATL's million-mile battery case study highlights the most promising of these solutions, **life extension by design.**

The Chinese battery manufacturer Contemporary Amperex Technologies Co., Limited (CATL) has recently launched a battery capable of covering a range of more than one million miles over its lifespan, known as Qilin (CATL, 2022). CATL affirmed that the new battery increases significantly the energy density to 255 Wh/kg for NMC battery systems while improving cooling performance fourfold (Energy Trend, 2022; Numerama, 2022). This new battery design enables the emergence of **new business models** while avoiding the environmental impacts associated with the production of new batteries.

Business model

Battery cycles have limits estimated at 1,000 to 2,000 full charges depending on literature sources and is evolving.

Alternatively, Qilin batteries can last for about 4,000 full recharges without degrading below commercial thresholds, creating potential for new business models such as **battery swapping and reselling.** A long-lasting battery could be particularly well suited for vehicles that remain in use for most of their lifespans, such as city buses, trucks, and taxis. Additionally, a million-mile battery could unlock **new symbioses** between e-mobility and decarbonised energy systems by permitting EVs to feed energy back into the grid when not in use (Los Angeles Times, 2020).

CATL currently supplies batteries to well-known OEMs like Mercedes-Benz, Volkswagen, Tesla, and Volvo, as well as local Chinese car manufacturers such as Nio, XPeng, and Li Auto (Les Echos, 2022). CATL declared in August 2022 they will start to produce the million-mile battery in 2023, and Zeekr would be the first brand using it for the model Geeley Zeeker 009. CATL has not made any updates at the time of this report.

Cost structure and Revenues

The sale price is expected to be around 10% higher than for the typical battery CATL currently sells (Los Angeles Times, 2020). Its use will depend on the evolution of battery performance and economics, and the width, range, power. Economists predict that consumers will be willing to **pay a premium for a high-performing battery** that can be easily replaced in a new vehicle, and will need to assess how much more consumers are willing to spend on this feature.

Social and Environmental benefits

A million-mile battery could drastically **reduce environmental pressures** generated by the extraction of raw materials (nickel, cobalt, manganese), refining, battery manufacturing and recycling, such as GHG emission and the pollution of land, soil, and water bodies.

Replicability potential

The Qilin battery is currently facing off the Tesla 4680 battery in the market. As the battery has not been supplied in large quantities, its technical abilities would need to be demonstrated at a wider scale. Lastly, a million-mile battery would lead to defining new business models to promote the battery swapping in several cars, possibly extend the impact on the lifespan of vehicles and scale-up the vehicle-to-grid solution.

3. DESIGNING OUT WASTE AND POLLUTION THROUGH INTEGRATED BATTERY DESIGN AND RECYCLING

The increasing amount of retired EVs and electronics has led to a corresponding rise in the number of end-of-life batteries. This, in turn, has become a significant environmental concern as the disposal of these batteries and e-waste is causing soil contamination and water pollution.

However, batteries and electronic waste can provide a **valuable secondary resource** as they contain elements and materials crucial for the manufacturing of EV batteries. Recycling these materials can potentially limit the reliance on imports from foreign primary markets, reduce the need for new conventional mines or increased mining intensity, and mitigate the negative environmental impacts associated with the disposal of end-of-life batteries.

The three solutions in this axis can integrate circularity into the last stage of the cobalt value chain through collection and recycling of e-waste and EV batteries. While all solutions reduce environmental and social pressures related to e-waste and battery disposal, **collection, sorting and recycling optimisation** appears to be the most feasible and impactful solution.

3.1. PROPOSED CIRCULAR SOLUTIONS

3.1.1. Use of recycled cobalt in battery design

Driven by policies and regulations such as the **EU Battery Regulation**, the required share of recycled *secondary* cobalt in batteries is increasing year after year and expects to reach 20% by 2035, limiting the need of primary cobalt for battery manufacturing and alleviating the pressure of global cobalt demand (European Commission, 2020).

At the time of this report, secondary cobalt is currently produced in small quantities each year, with most of it coming from recycled batteries (65%), tungsten carbide (24%), and alloy scraps and catalysts (11%) (Roskill, 2021). However, the secondary sourcing of cobalt is expected to **scale up** as a result of EV battery recycling, replacing about 25% of the total demand by 2040 (KU Leuven, 2022). As more EV batteries are recycled, **the price of recycled cobalt**, which is currently higher than primary cobalt, **is expected to decrease.**

For the integration of recycled cobalt in battery design to be widely put in place, **traceability** of secondary cobalt should be improved, as there is significant potential for illegal ASM cobalt to be disguised as secondary cobalt. For this reason, downstream stakeholders should conduct supply chain audits and significant investments should be made into different traceability technology solutions such as the blockchain solution developed by The Circulor platform to trace material flows, analysing data and detecting potential incoherences while maintaining confidentiality (Johnson-Poensgen, 2022).

Integrating recycled cobalt into future products will eventually depend on its availability. However, if scaled up, it can have significant environmental benefits by **avoiding the production of primary cobalt production**, as well as the **disposal of e-waste and scrap batteries,** reducing soil and water contamination. Environmental assessment studies indicate that GHG emissions from the recovery of cobalt sulphate through pyrometallurgy are important and might even be comparable to primary cobalt, while hydrometallurgical recycling offers relative environmental advantages. However, boundaries between LCAs differ, leading to significant variation ranges, and it remains to be seen whether substituting primary production with secondary production reduces significantly enough the associated GHG emissions.

3.1.2. Collection, sorting, and recycling optimisation

By optimising the collection, sorting, and recycling processes, it is possible to fully utilise e- waste and retired EV batteries, becoming valuable resources rather than disposable waste.

The collection of batteries and e-waste have so far been low, with only 17% of global e-waste documented to be collected (Baldé, D'Angelo, Luda, Deubzer, & Kuehr, 2022). Therefore, collection infrastructures and services need to be better developed to increase the amount of electronic waste that is being fed into the recycling schemes.

Apart from an ineffective collection, the current recycling rate of cobalt remains low, which is mainly due to the high diversity of feedstocks containing cobalt as well as a complex recycling process that lacks flexibility and adaptation to these feedstocks. A **more tailored approach to cobalt recycling** is therefore required to maximise its potential (Church & Wuennenberg, 2019).

Once the batteries and e-waste collected, it is crucial to ensure efficient recycling by selecting an **appropriate recycling process tailored** to the specific type of feedstocks. **Hydrometallurgy** can be well-suited for uniform waste streams such as battery manufacturing scrap and end-of- life EV batteries, while **pyrometallurgy** can be better suited for diverse electronic waste (Baum, Bird, Yu, & Ma, 2022). **Combining both** metallurgical methods into one tailored process can also help enhance recovery rates. Regardless of the process, **sorting batteries before recycling** them is a critical step in ensuring optimal recycling (Cardoso, 2022).

Collection, sorting and recycling optimisation can **increase the collection and recycling rates** of EV batteries and electronic products, preventing their disposal in landfills and **minimising the air, soil and water pollution** associated with it. This approach has a great scaling potential thanks to a continuous effort to improve process efficiency through technological advancement.

3.1.3. Battery as a service and other battery return schemes

New business models are emerging for e-waste and EV battery regarding their collection and treatment at end-of-life, where the OEMs can keep ownership of their products and cycle them directly back into their manufacturing.

One of these business models is **the battery as a service (BaaS)** which is increasingly becoming a subject of interest for OEMs in the automotive industry. Rather than purchasing and owning a new vehicle along with its own lithium-ion battery pack, OEMs provide their customers the option to **lease the battery as a separate component from cars** or to **subscribe to a battery subscription plan**, providing them with a cost-effective alternative.

Other battery return schemes could also be developed to recover electronic goods through incentive campaigns (vouchers) while **creating financial values** for consumers. For these models to grow, collection infrastructure and services will need to expand to improve collection.

Establishing battery return schemes and improving collection rates can **limit the pollution from battery disposal.** However, adopting these business models presents some challenges, in particular a lack of clear regulations to improve current collection infrastructures and services.

3.2. CASE STUDY OF MOST PROMISING CIRCULAR SOLUTION: FAIRPHONE E- WASTE NEUTRALITY INITIATIVE

All three circular solutions described in this section offer economic, social and environmental benefits to the cobalt value chain. The following case study of Fairphone's e-waste neutrality initiative focuses on an improved electronic waste collection, highlighting a key aspect of the most promising of the three circular solutions.

Fairphone is a Dutch smartphone producer that designs responsible modular phones, allowing for **longer lifetime and post-life refurbishment or recycling.** The company has committed to make their phone model *Fairphone 4* as well as their *True Wireless Earbuds* **e-waste neutral**, meaning that for each of those sold devices, another discarded phone or the same amount of e-waste is either reused or recycled through Fairphone's efforts.

To fulfil this commitment, Fairphone has developed several programmes, including the waste compensation model through which the company partners with actors like Closing the Loop that collect and recycle electronic end-of-use products from countries in West Africa with insufficient recycling infrastructure. On top of that, Fairphone allows users to send in their old phones, whether it's a Fairphone or any other brand. Recovered phones that can be refurbished are resold for a second lifecycle, while the others are recycled if possible, aiming to reintegrate secondary materials into electronics and other supply chains (Fairphone, 2022).

Business model

For the last couple of years, Fairphone has been exploring new business models that position the company as a leader in circular economy among smartphone providers. Through their **Reuse and Recycle Programme**, used phones are recovered, refurbished and sold at a profit, covering the costs of shipment and repair. Currently, recycling the non-reusable phones represents a cost to the company, but can potentially allow for the recovery of spare parts that are in good condition. By showcasing this new circular solution through partnerships, Fairphone also gains a **better reputation** and can unlock **new potential customers** (Fairphone, 2022).

The company also introduced Fairphone Easy, a **monthly subscription service** in which users rent their devices and are rewarded with lower monthly fees for keeping their phone longer and in good condition. By leasing the phone instead of selling it, Fairphone ensures optimal use of resources over the course of the phone's life and stays in control of giving it a second life or recycling it (Fairphone, 2022).

Environmental and social benefits

The initiatives undertaken by Fairphone have several environmental benefits, including limiting the need for primary materials with improved resource efficiency and limiting the pollution generated from e-waste incineration or disposal in landfills. Through the launch of different programmes, **8 tonnes of e-waste were avoided in 2021.** In addition, through longer phone lifetime, reuse and recycling, Fairphone also improves resource efficiency.

Fairphone chooses to **engage stakeholders** in higher risk areas in order to have a greater positive impact, including planning to work in the future in Ghana to develop **capacity building programmes** for e-waste collection, where unsafe and informal recycling practices can have harmful impacts on people and the environment.

Replicability potential

As mentioned in section 3.1.2, the global collection rate of e-waste was only 17% in 2019, with the **remaining undocumented 83%** either dumped, illegally exported, or informally recycled, representing a huge potential for collection (Baldé, D'Angelo, Luda, Deubzer, & Kuehr, 2022). Implementing take-back schemes and waste compensation models similar to those taken by Fairphone can bring substantial reputational benefits to companies, even if they must operate at a cost.

Currently, the volumes of e-waste collected through Fairphone' compensation initiative are limited, presenting a challenge to companies like Fairphone when it comes to selecting service providers who have a suitable set up and are willing to collaborate. Nevertheless, through careful engagement with collectors and with the support of appropriate policies, the potential for replicating this approach can be further increased.

4. CONCLUSIONS

Through its three circularity axes, this study provides a vision of a circular cobalt value chain capable of creating shared value for people and the planet. Each circular solution shows how shifting towards a circular economy can help the cobalt industry directly confront its salient social and environmental risks, while also creating additional value for both cobalt producers and consumers. Across all three areas of focus, several crosscutting themes emerged, which are presented below as key conclusions.

The need for all circular solutions beyond recycling

The shift to a circular, steady-state, economy will be a continuous process. As has been noted, **vast amounts of primary cobalt will be needed** in the coming decades to cover **increased demand for climate-smart technologies**, particularly **energy storage in e-mobility**. EV batteries with cobalt cathodes are expected to have lifespans of between 8 and 15 years, and lithium-ion battery demand is growing exponentially. Thus, even by 2040, only an estimated 25% of global cobalt demand will be able to be met by secondary cobalt (KU Leuven, 2022). Over the longer term however, the increased numbers of batteries reaching their end-of-life will enable improved recycling systems and the percentage share of secondary cobalt in the market will grow.

This need to grow cobalt stocks within the global economy within the medium term means that **stakeholders must expand their vision of circularity beyond simply recycling.** There is a strong need for a circular economy strategy capable of recovering cobalt where it is currently lost to waste streams, while also maximising the value of cobalt products in use.

To conclude, we wish to bring forward five concrete actions, highlighted in Table 1, for industry leaders and policy makers to build out a circular cobalt value chain.

Table 1. Key recommended actions

1. DESIGN AND IMPLEMENT NEW POLICIES
• National mining codes and assaying requirements should be updated to promote best practices in mine waste valorisation • Stronger policies are needed to enable safe and sustainable battery re-use • Consumer protection regulations and product standards (such as the EU battery regulation) are important mechanisms to promote eco-design of durable and sustainable cobalt containing products • International collaboration between cobalt production and cobalt consuming countries will be essential to ensure circularity at each stage in the value chain, in line within international biodiversity and climate goals

2. ELIMINATE WASTE AT EXTRACTION AND END-OF-LIFE

- Tackle feedstock complexity with improved ore and battery sorting
- Strive to recover all by-product materials at the mine and recycling plant
- Improved cobalt recovery from mine and battery waste should happen with respect for the rights of workers in both the formal and informal economy
- Improve collection schemes of e-waste to capture significant value

3. MAXIMISE THE VALUE OF COBALT USE

- Design durable cobalt products to reduce environmental pressures
- Battery design should incorporate trade-offs between easy dismantling and battery performance
- Adapt to a rapidly evolving and growing market for battery repurposing

4. EXPLORE NEW BUSINESS MODELS

- Tailings should no longer be considered as waste with a cost, but rather by-products capable of generating value
- Battery as a Service and other battery rental schemes can create shared value for OEMs and consumers, while also enabling repurposing and recycling
- As the increasing amounts of cobalt containing products reach their end-of-life in coming decades, cobalt refiners can drive circularity by transitioning from primary to secondary cobalt feedstocks

5. USE DATA TO UNLOCK CIRCULAR OPPORTUNITIES

- Gather and share open-source data related to tailings composition and suitability for reprocessing or mineral carbonation
- There is a need for clear comparative metrics on the performance of different battery chemistries during their in-use phase
- Traceability across primary and secondary cobalt supply chains, along with information about battery health can promote circularity

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APPENDIX - LIST OF INTERVIEWED ORGANISATIONS AND EXPERTISE

Table 2. List of interviewed organisations and expertise

NAME OF THE PERSON	ORGANISATION	EXPERTISE
Renata Cardoso	Electra BMC	Cobalt refining and ESG
Claude Chanson	RECHARGE	European battery market
Bryony Clear Hill	ICMM	Responsible mining standards
Mickael Daudin (Note: no longer employed at Pact)	Pact	ASM mining
Andrew Gulley	USGS	Geology
Douglas Johnson-Poensgen	Circulor	Supply chain traceability
Angela Jorns	Fairphone	Electronics manufacture
Joe Kaderavek	Cobalt Blue	Cobalt mining
Yu-Hsuan Kang	Fairphone	Electronics manufacture
Thea Kleinmagd	Fairphone	Electronics manufacture
Clémence Siret	Saft	Battery design & recycling
Barend Ubbink	In2Waste Solutions	Circular economy
Craig Woodburn	BritishVolt	Battery cell manufacture
Jared Zhu	SMM	Chinese metals market
Anonymous	Electric Vehicle OEM	Battery materials and circular economy

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